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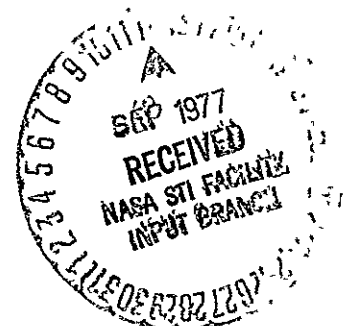
COHERENCE AND PHASE TECHNIQUES APPLIED TO NOISE SOURCE DIAGNOSIS IN THE NASA AMES 7 x 10-FOOT WIND TUNNEL NO. 1

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J. F. Wilby
A. G. Piersol
P. E. Rentz
T. D. Scharf

18 July 1977

Submitted to:
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035



National Aeronautics and
Space Administration



Ames Research Center
Moffett Field, California
94035

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Baltimore/Washington International Airport,
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Ralph W. Lewis

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COHERENCE AND PHASE TECHNIQUES APPLIED TO NOISE SOURCE
DIAGNOSIS IN THE NASA AMES 7x10 FOOT WIND TUNNEL NO. 1

J. F. Wilby
A. G. Piersol
P. E. Rentz
T. D. Scharton

18 July 1977

Submitted to:
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

ABSTRACT

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Measurements have been made of coherence and phase spectra for the acoustic field in a subsonic wind tunnel. The data are interpreted in terms of simple analytical models for propagating and diffuse noise fields, including the presence of uncorrelated noise signals. It is found that low frequency noise propagates upstream and downstream from the fan, with the noise in the test section arriving in the upstream direction. High frequency sound appears to be generated in the test section and propagates upstream and downstream. In the low frequency range, the ratio of diffuse to propagating energy is about 8 for all locations in the test section, diffuser, and settling chamber; the value of the ratio increases with frequency. Further analysis is required to describe in better detail the effects of reverberation and incoherent sources in a duct-like environment.

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1. INTRODUCTION

In recent years there has been an increasing need to use wind tunnels as acoustic test facilities. As a consequence, modifications have become necessary to convert tunnel test sections into suitable acoustic environments. One such conversion is planned for the NASA Ames Research Center 7x10 foot #1 Wind Tunnel. Before designing the modifications for the tunnel, acoustic surveys were performed to determine reverberation characteristics and to identify noise sources for subsequent noise control treatment. As part of the investigation, acoustic coherence and phase spectra were measured at several locations within the tunnel. These spectra were then interpreted in terms of relative contributions from propagating and diffuse components in the tunnel noise field. This report presents a summary of the investigation, describes the problems associated with data interpretation, and presents conclusions regarding the sources of noise in the tunnel test section.

2. WIND TUNNEL NOISE LEVELS

The NASA Ames 7x10 foot #1 wind tunnel is a subsonic recirculating flow tunnel with a single stage fan. A schematic of the tunnel is shown in Figure 1. The tunnel circuit is closed, with the exception of an interchange section downstream of the fan. An acoustic survey [1] of the tunnel was conducted in 1975 with the purpose of identifying noise sources so that noise control features could be installed. The survey concluded that a large percentage of the acoustic energy in the test section was generated by struts, airfoils and other protuberances located in the test section or the entry to the diffuser. This conclusion was validated, to some extent, by later measurements of Soderman [2], who was able to reduce the sound levels in the test section by removing some of the protuberances and sealing holes in the wall of the test section. However, at mid and high frequencies, the measured levels still exceeded values predicted for the fan alone (Figure 2). Thus it was decided to explore the use of coherence and phase measurements for identifying the noise sources in the test section.

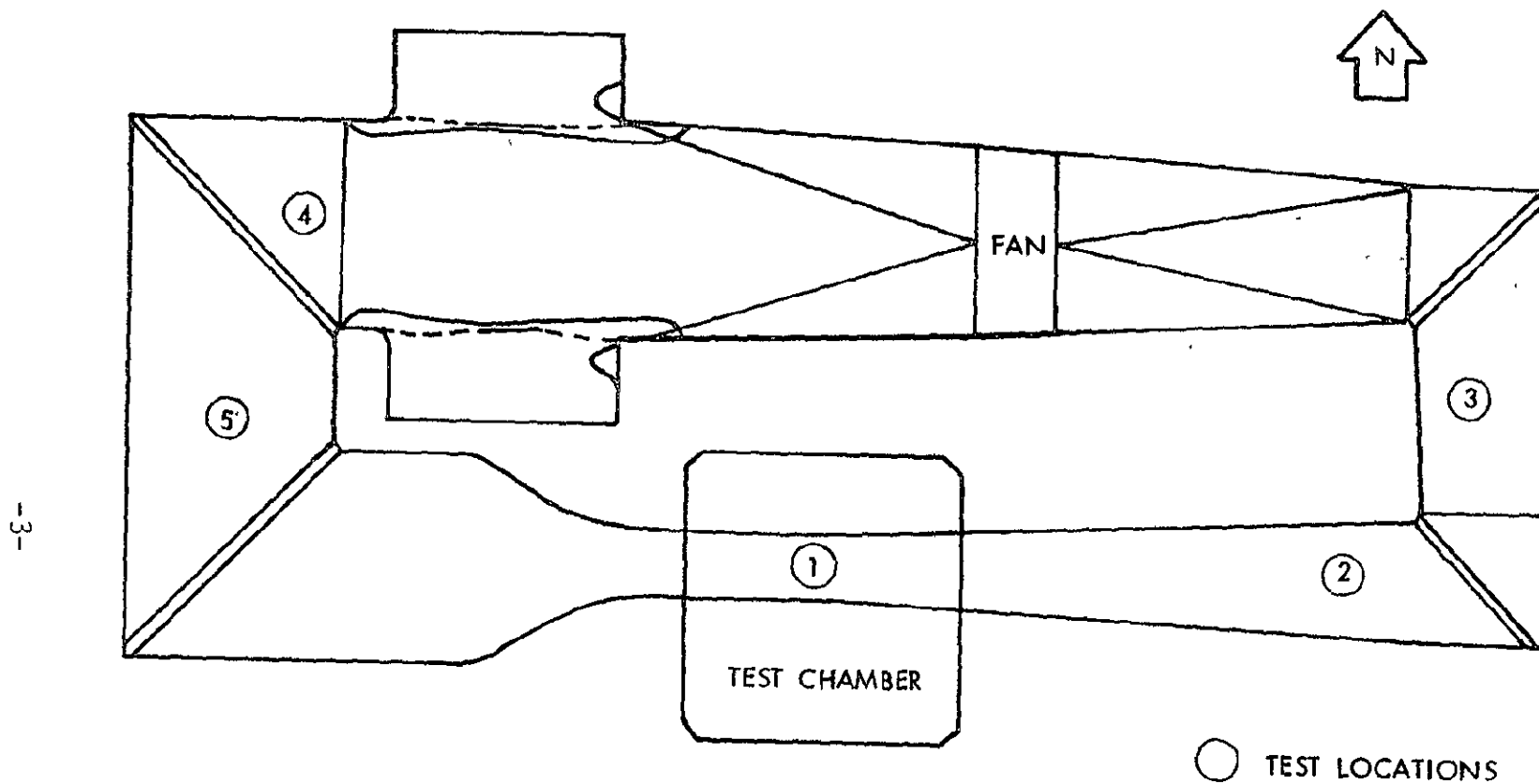


FIGURE 1. DIAGRAM OF 7' x 10' WIND TUNNEL

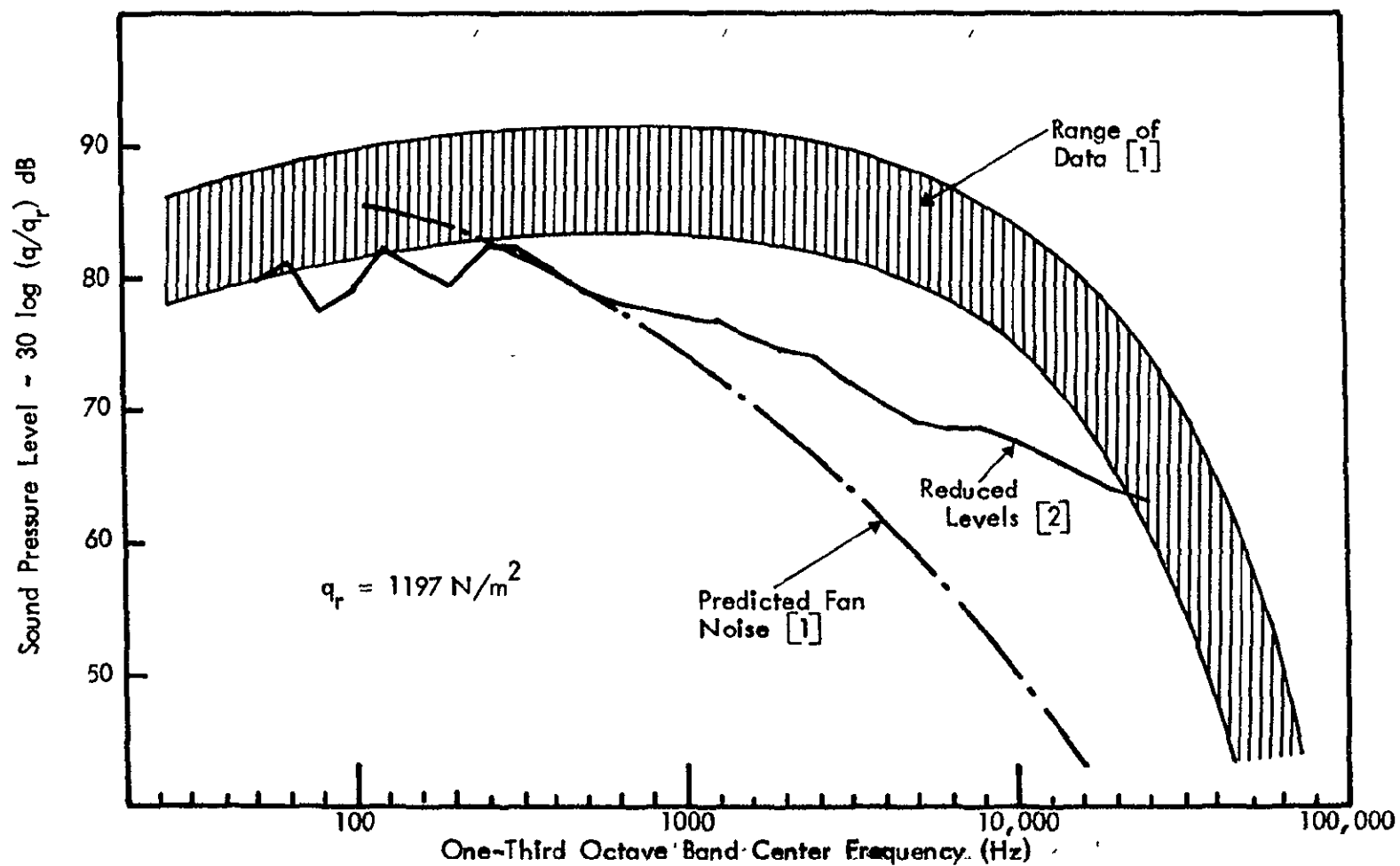


FIGURE 2. NOISE SPECTRA IN TUNNEL TEST SECTION

3. COHERENCE AND PHASE FUNCTIONS

The noise field in the wind-tunnel could consist of contributions from propagating, diffuse and reverberant sound fields. For example, noise from the tunnel drive fan could propagate into the diffuser and settling chamber, and be influenced by the reverberant characteristics of those regions of the tunnel. Also the boundary layer in the test section would radiate sound, and individual regions of the boundary layer could be considered as incoherent sources, thereby generating a diffuse field. Since it is the intention of this report to compare measured coherence and phase spectra with possible analytical models, it is necessary to review the analytical representations associated with the different sound fields.

Consider first the case of propagating waves, and include the influence of incoherent noise, such as may be introduced by aerodynamic self-noise on the microphone diaphragms. The cross power spectral density function for a single propagating wave can be written as

$$G_{xy}(f) = G_p(f)[\cos \phi + i \sin \phi] \quad (1)$$

where it is assumed that the power spectral densities of the signal at positions x and y are equal (i.e., there is no attenuation between the two observation points).

$$\text{Thus } G_x(f) = G_y(f) = G_p(f)$$

and the phase angle ϕ is given by

$$\phi = \phi(f) = kd \quad (2)$$

where k is the wave number $2\pi f/c$, d is the distance between the two measurement locations, and $c = c_0/\cos \theta$ is the trace wave speed along the axis joining the two measurement locations (Figure 3).

If the self noise on each microphone has a power spectral density $G_n(f)$, and the noise signals are uncorrelated, the coherence function is

$$\gamma^2(f) = \frac{G_p^2(f)}{[G_p(f) + G_n(f)]^2} \quad (3)$$

and the phase angle is $\phi(f)$ as given by eqn. (2). The uncorrelated noise reduces the coherence but does not affect the phase.

Now, introduce a second propagating wave of the same frequency, under assumptions that the waves are nondispersive, that they are independent and uncorrelated with respect to each other, and that the initial phases associated with each wave are uniformly distributed from $-\pi$ to $+\pi$. Then, dropping the f notation for convenience,

$$\gamma^2 = \frac{G_1^2 + G_2^2 + 2G_1G_2\cos(\phi_1 - \phi_2)}{(G_1 + G_2 + G_n)^2} \quad (4)$$

$$\text{where } \phi_i = \frac{2\pi f d}{c_i}, \quad c_i = \frac{c_0}{\cos \theta_i}$$

$$\text{and } \phi = \tan^{-1} \left[\frac{G_1 \sin \phi_1 + G_2 \sin \phi_2}{G_1 \cos \phi_1 + G_2 \cos \phi_2} \right] \quad (5)$$

Here G_1, G_2 are the power spectral density functions for the two waves and ϕ_1, ϕ_2 the corresponding phase angles. Since $-1 \leq \cos(\phi_1 - \phi_2) \leq +1$, γ^2 lies in the range

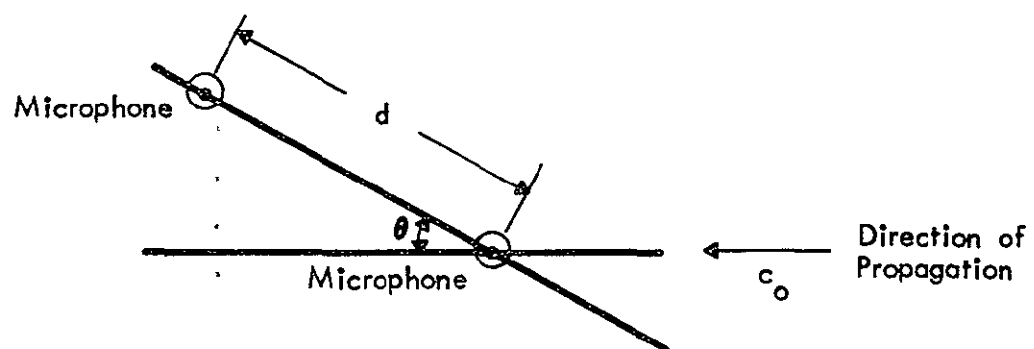


FIGURE 3. GENERAL ARRANGEMENT OF TRANSDUCERS

$$\frac{(G_1 - G_2)^2}{(G_1 + G_2 + G_n)^2} \leq \gamma^2 \leq \frac{(G_1 + G_2)^2}{(G_1 + G_2 + G_n)^2} \quad (6)$$

and has a periodicity of π with respect to $(\phi_1 - \phi_2)$.

Markowitz [3] has considered several specific cases for γ^2 and ϕ , and has described the problems which can arise in measurement interpretation. Some of the cases are discussed below.

For two waves of equal magnitude G_p , traveling in the same direction

$$\gamma^2 = \frac{2 + 2 \cos(\phi_1 - \phi_2)}{(2 + G_n/G_p)^2} \quad (7)$$

and

$$\phi = \frac{\phi_1 + \phi_2}{2}$$

Values of ϕ are shown in Figure 4 for several values of the ratio ϕ_2/ϕ_1 , and it is seen that ϕ follows a linear relationship with ϕ_1 .

The effective trace velocity for the combined signal is given by

$$\frac{1}{c} = \frac{1}{c_1} + \frac{1}{c_2} \quad (9)$$

In general the two waves will have different magnitudes, and

$$\phi = \tan^{-1} \left\{ \frac{[G_1/G_2 + \sin \phi_2 / \sin \phi_1]}{[G_1/G_2 + \cos \phi_2 / \cos \phi_1]} \tan \phi_1 \right\} \quad (10)$$

It can be assumed, without loss of generality, that $G_1 > G_2$. In the extreme case, if $G_1 \gg G_2$ then $\phi \rightarrow \phi_1$. Alternatively, if $G_1 \approx G_2$,

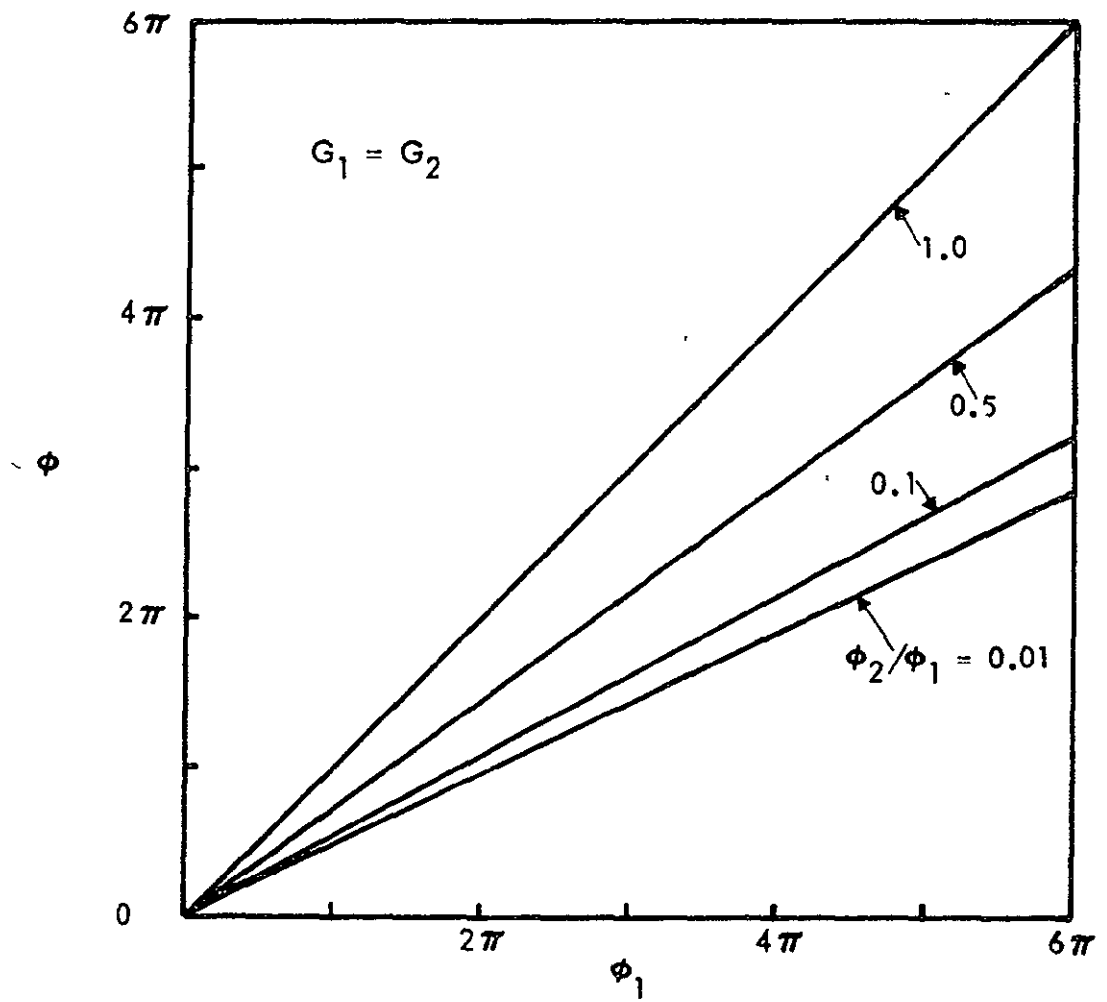


FIGURE 4. PHASE FOR EQUAL MAGNITUDE WAVES TRAVELING IN SAME DIRECTION: EFFECT OF ϕ_2 / ϕ_1 [3]

$\phi \rightarrow \frac{\phi_1 + \phi_2}{2}$, which was obtained above (equation 8). However if $G_1/G_2 = 0(1)$ and $\phi_2/\phi_1 < 1$, ϕ exhibits periodic variations about $\phi = \phi_1$. The periodicity of ϕ with respect to ϕ_1 is $2\pi \left[\frac{1}{1 - \phi_2/\phi_1} \right]$, or in terms of frequency, f , the periodicity is

$$\Delta f = \frac{1}{d} \left(\frac{c_1 c_2}{c_1 - c_2} \right) \quad (11)$$

Typical patterns for coherence and phase angle spectra associated with two propagating waves are shown in Figure 5. Two systems are considered. In one case waves $G_1 = 3$, $G_2 = 1$ are traveling in the same direction with $\phi_2/\phi_1 = 2.5$, and in the other case waves $G_1 = 3$, $G_2 = 1$ are traveling in opposite directions with $\phi_2/\phi_1 = -0.5$. For both cases the incoherent noise input, G_n , is zero. The coherence functions are identical for the two cases, oscillating between lower and upper bounds of 0.25 and 1.0 (see eqn. (4)) with periodicity $4\pi/3$ with respect to ϕ_x . Phase angle spectra also have a periodicity of $4\pi/3$, but there is a half period phase shift between the two curves. Examples of wave combinations are discussed by Markowitz [3], including several cases of ambiguity.

Now consider the combination of a diffuse field with a propagating wave and self noise. The cross power spectral density for the diffuse field is

$$G_{xy}(f) = G_d(f) \frac{\sin \phi_o}{\phi_o} \quad (12)$$

$$\text{where } \phi_o = k_o d = \frac{\omega d}{c_o} \quad (13)$$

and c_o is the ambient speed of sound.

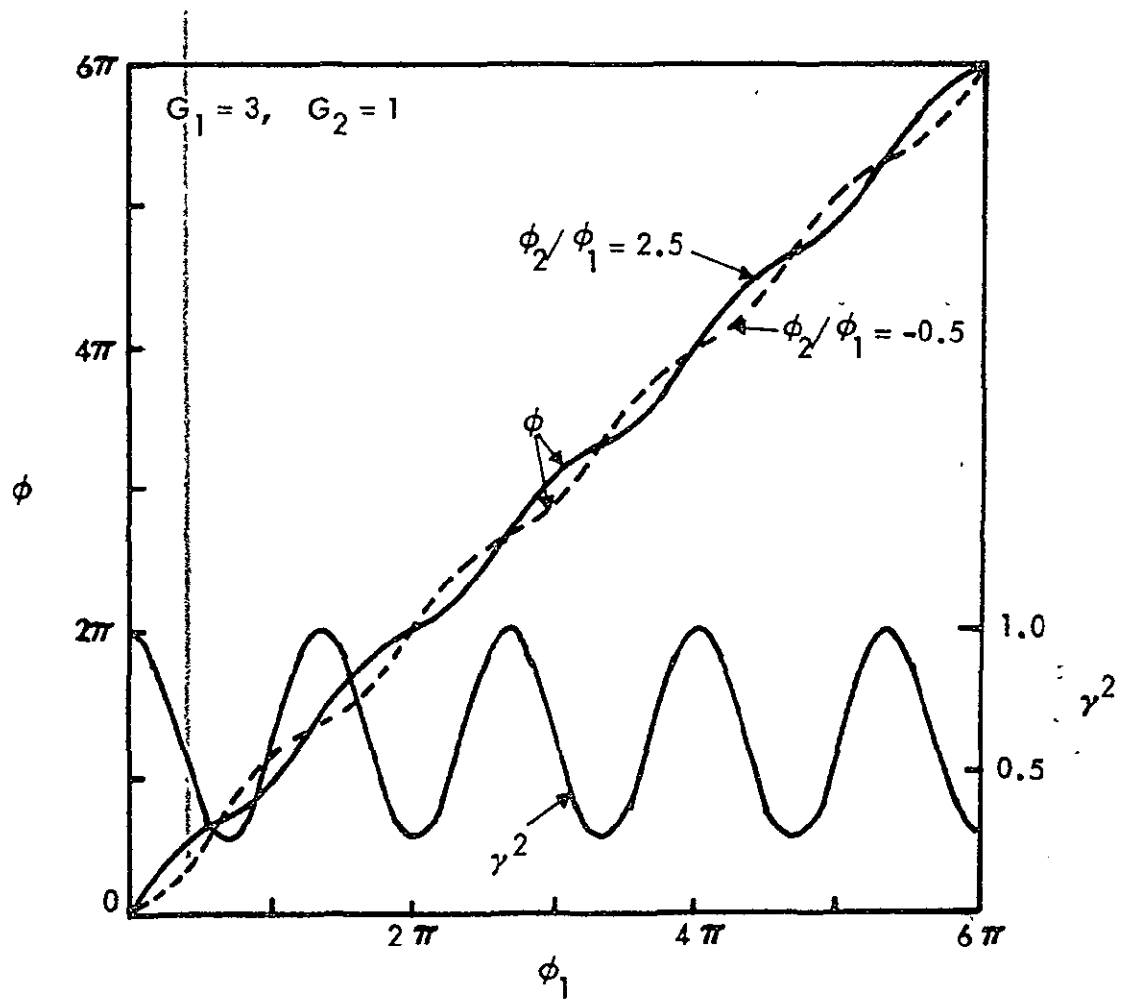


FIGURE 5. EXAMPLE COHERENCE AND PHASE SPECTRA FOR PROPAGATING WAVE PAIRS [3]

$$\text{Then } \gamma^2 = (1 + R + G_n/G_p)^{-2} \left\{ \left(\frac{R \sin \phi_0}{\phi_0} + \cos \phi_1 \right)^2 + \sin^2 \phi_1 \right\} \quad (14)$$

$$\text{and } \phi = \tan^{-1} \left[\frac{\sin \phi_1}{R \frac{\sin \phi_0}{\phi_0} + \cos \phi_1} \right] \quad (15)$$

where R is the ratio of the diffuse and propagating power spectral densities, $R = G_d/G_p$. Again, uncorrelated noise affects only the coherence. The form of γ^2 and ϕ can now be demonstrated by means of sample non-dimensional plots.

Figures 6 and 7 show coherence and phase spectra for the case $G_n = 0$, and $\theta = 0$, (i.e., $\phi_0 = \phi_1$), for a series of values of R . The coherence decays asymptotically to a value $(1 + R)^{-2}$ instead of the value of unity for a propagating wave alone, or zero for a diffuse field. The phase follows the basic characteristics of a propagating wave but deviates by an amount dependent on R and ϕ_1 . As ϕ_1 increases, $\frac{\sin \phi_1}{\phi_1} \rightarrow 0$ and the phase ϕ tends to the propagating wave relationship.

It will be noticed that the deviations are always such that ϕ lags behind ϕ_1 , and that they repeat with period π . If however θ is non-zero, the periodicity of $\sin \phi_0$ differs from that of $\sin \phi_1$ and the resulting periodicity of ϕ is no longer π with respect to ϕ_1 . An example is shown in Figures 8 and 9 where γ^2 and ϕ are plotted for $\theta = 0$ and $\pi/4$, with $R = 8$. For ϕ , in particular, it is observed that ϕ may now lead or lag ϕ_1 .

Consider now the effect of introducing a mean flow velocity U , such as would be present in the wind tunnel. For a combination of propagating waves, c_i becomes

$$c_i = c_0 / \cos \theta_i + U / \cos \alpha_i \quad (16)$$

where the angles are defined in Figure 10.

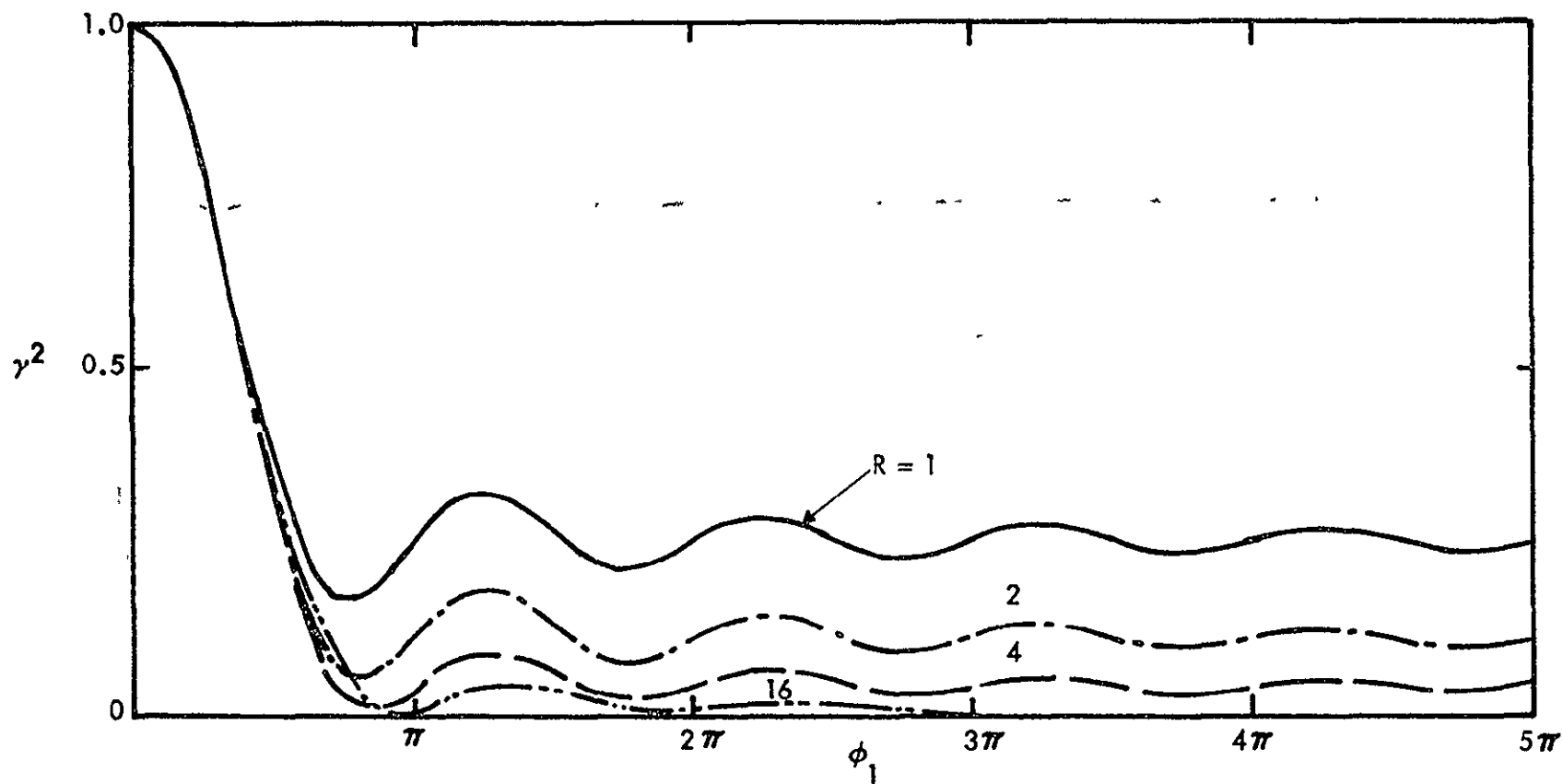


FIGURE 6. EFFECT OF R ON COHERENCE SPECTRUM ($U = 0, \theta = 0$)

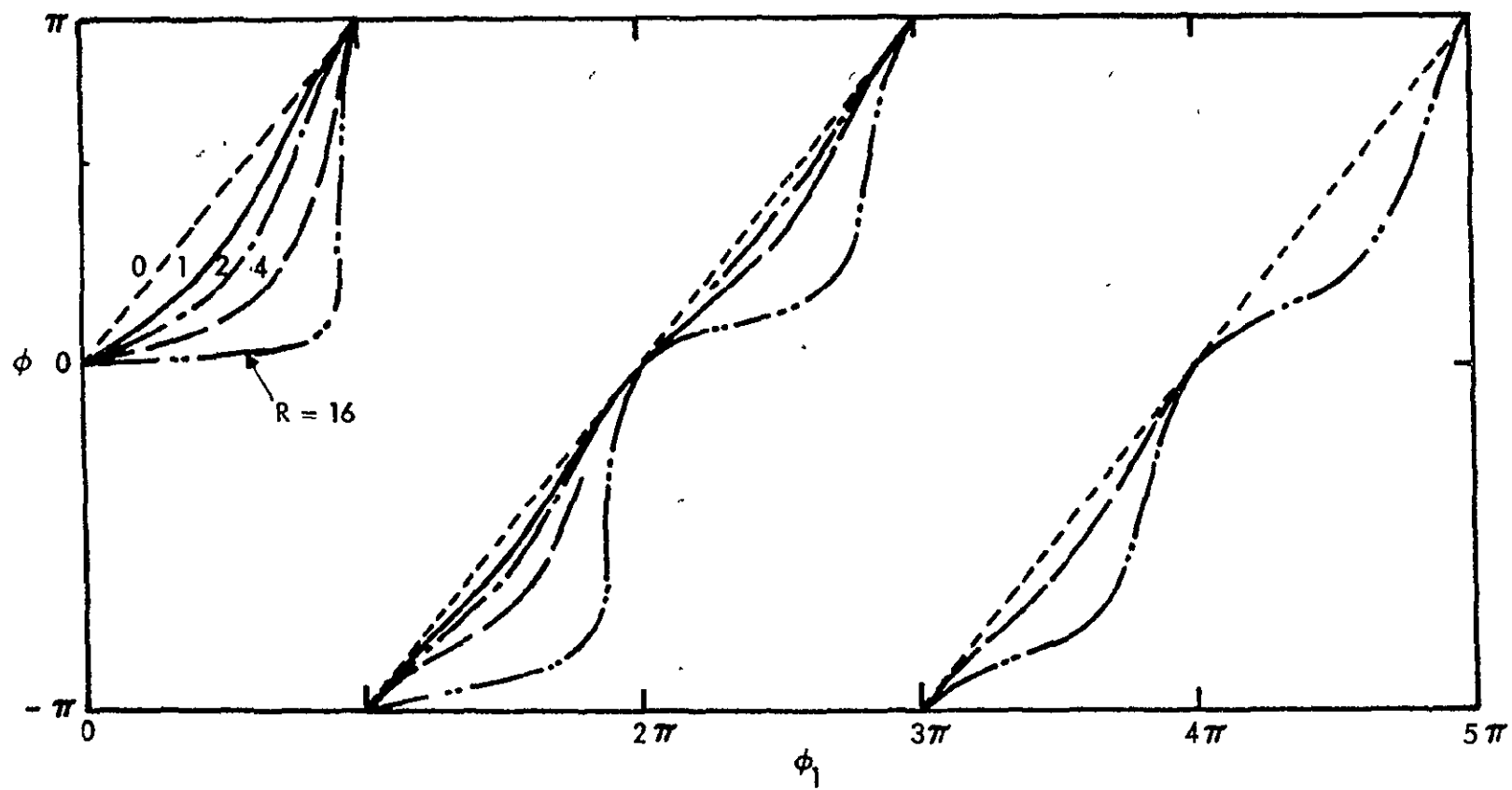


FIGURE 7. EFFECT OF R ON PHASE SPECTRUM ($U = 0$, $\theta = 0$)

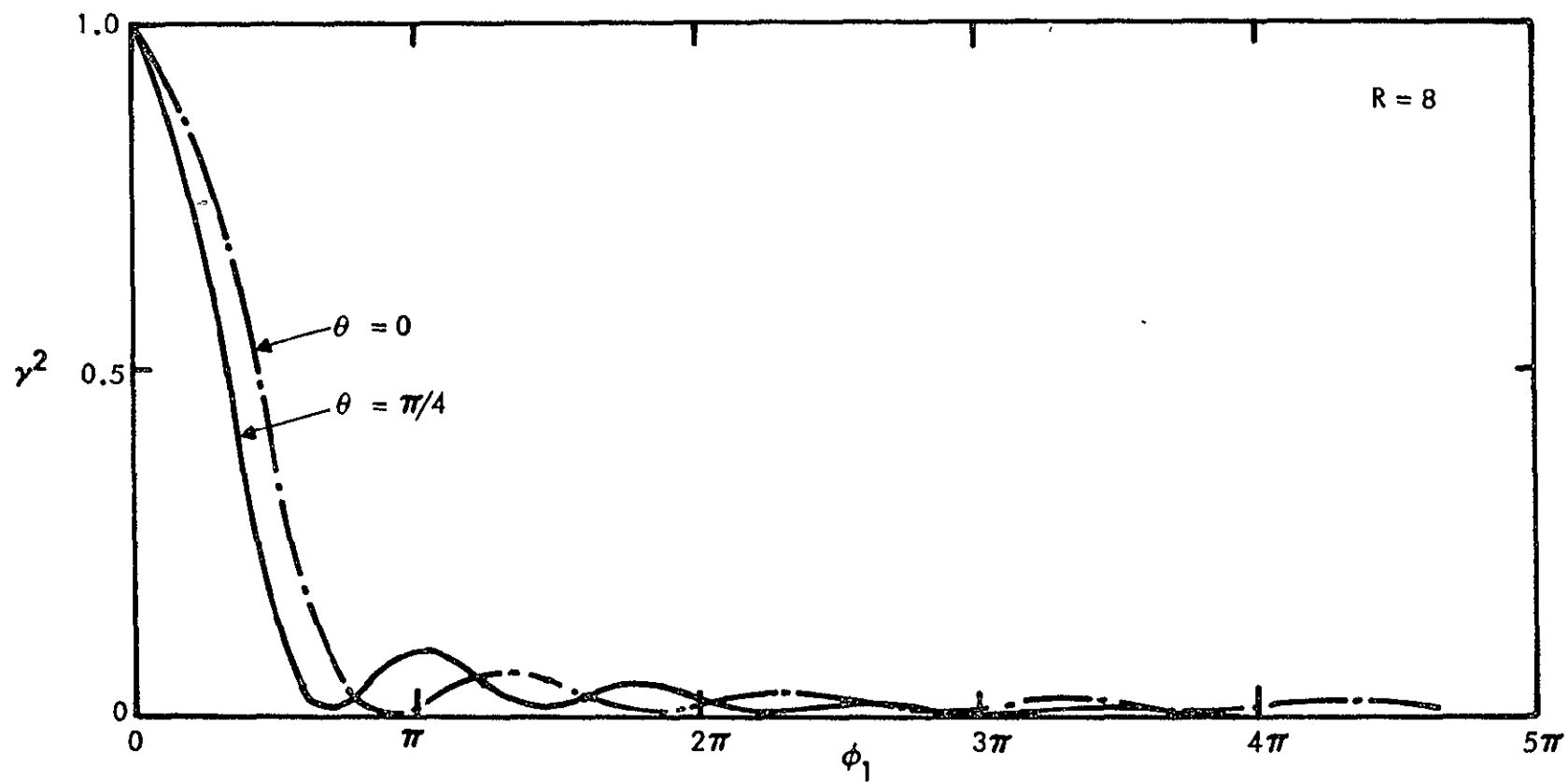


FIGURE 8. EFFECT OF θ ON COHERENCE SPECTRUM ($U = 0$)

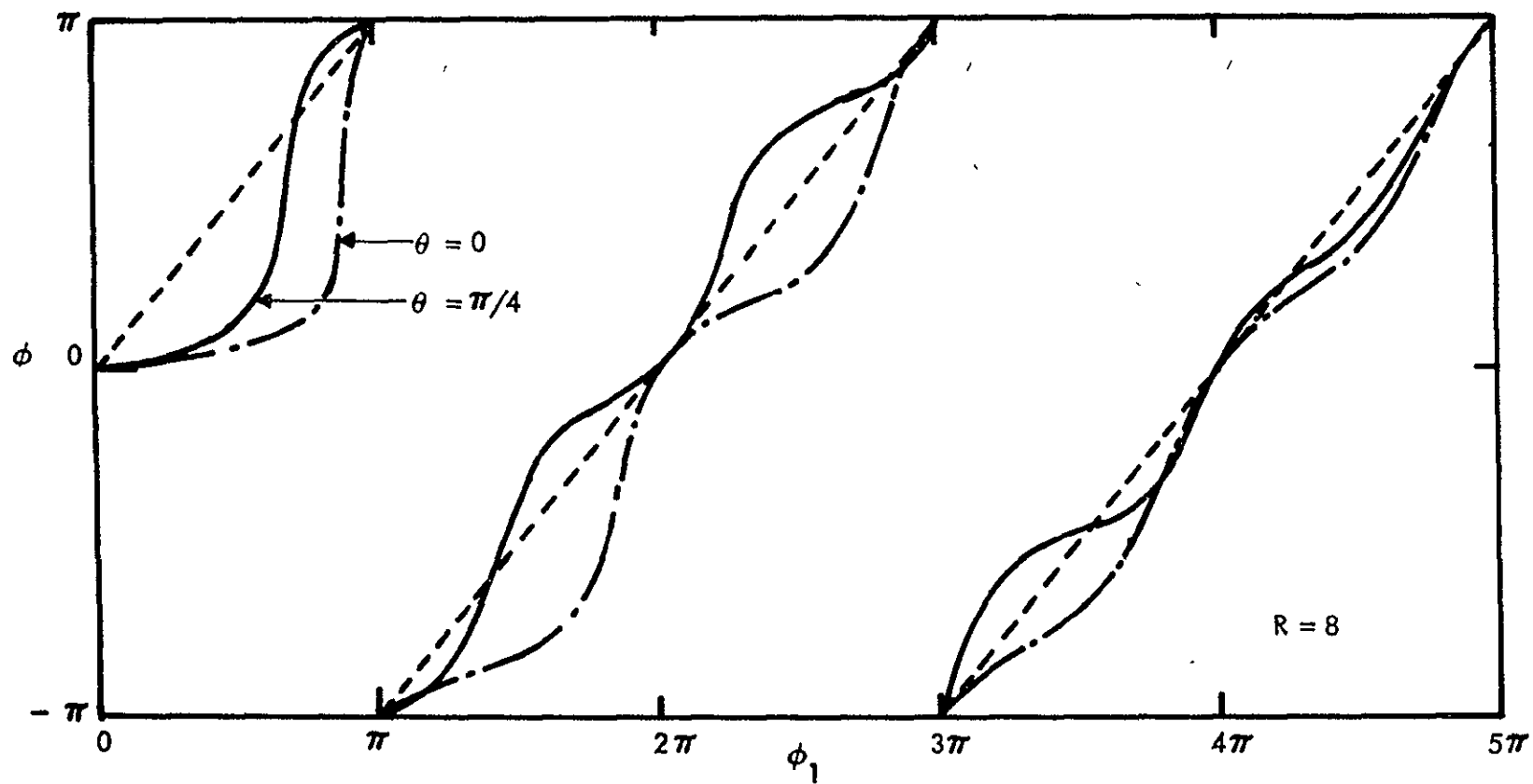


FIGURE 9. EFFECT OF θ ON PHASE SPECTRUM ($U = 0$)

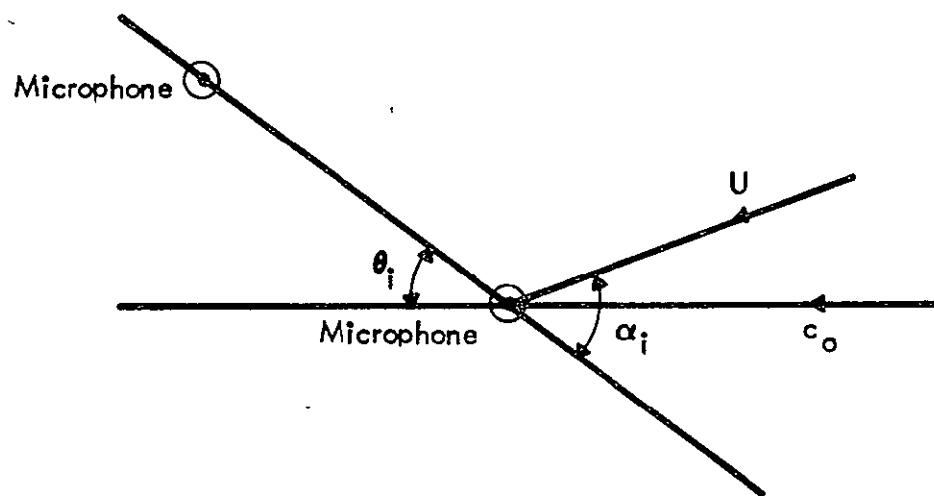


FIGURE 10. GENERAL ARRANGEMENT OF TRANSDUCERS WITH FLOW

For a combination of diffuse and propagating waves, the situation is a little more complicated. If it is assumed that, on the average, the representation of the diffuse field is unaffected by the superimposed mean flow, then the diffuse term remains $\frac{\sin \phi_o}{\phi_o}$. The propagating phase ϕ_1 will, however, be modified by the mean flow as before.

$$\phi_1 = \frac{\omega d}{c_1} \text{ where } c_1 = \frac{c_o}{\cos \theta_1} + \frac{U}{\cos \alpha_1} .$$

If it is assumed that the wave is propagating in the direction parallel to the mean flow

$$\alpha_1 = \theta_1 \text{ or } (\theta_1 + \pi) ,$$

depending on whether the propagation direction is downstream or upstream, and

$$c_1 = \frac{(c_o \pm U)}{\cos \theta_1} = c_o \frac{(1 \pm M)}{\cos \theta_1}$$

In this case the net effect on γ^2 and ϕ will be similar to those produced by a change in the value of θ_1 . For example, a flow Mach number of 0.1 will have the same effect as a 10% change in $\cos \theta_1$.

Thus far, the discussion has assumed that the acoustic waves are freely propagating and statistically independent such that the initial phase can be taken at random with a uniform distribution from $-\pi$ to π . If it is now assumed that two acoustic waves of equal magnitude and wave number are propagating in opposite directions, and that the waves are not statistically independent but have an initial phase of zero, then the two waves combine to give a standing wave. The coherence function is then -

$$\gamma^2 = \left| \frac{\cos(kx_1)\cos(kx_2)}{|\cos(kx_1)| |\cos(kx_2)|} \right|^2 \quad (17)$$

where x_1, x_2 are the two measurement locations, and

$$\left. \begin{aligned} \phi &= 0 \text{ (in phase)} \\ &= \pi \text{ (out of phase)} \end{aligned} \right\} \quad (18)$$

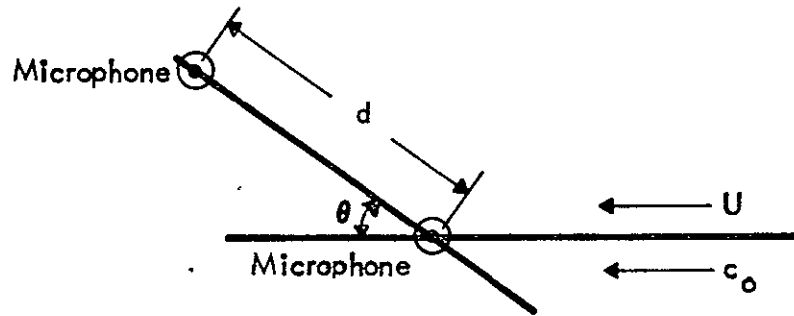
Extending this argument to the noise field associated with a single noise source in a reverberant enclosure, it is found that the coherence is again unity, provided that a sufficiently long integration time (of the order of the reverberation time) is used in the analysis [4,5].

4. TEST PROGRAM

Acoustic measurements were made at five general locations in the wind tunnel test section, diffuser and settling chamber. The locations are identified in Figure 1. At each location two Bruel and Kjaer 1/2 inch microphones with nose cones were mounted on 1.8 m (6 ft) high stands. One microphone was placed upstream of the other, but, to minimize wake interference between microphones, the microphone locations were staggered relative to the flow direction. Typical arrangements are shown in Figure 11.

Acoustic signals from the pair of microphones were analyzed using a Spectral Dynamics Model SD 360 Signal Processor, with Spectral Dynamics Model 332 Translator being used in conjunction with the SD 360 in some cases. Data reduction consisted mainly of coherence and phase angle spectra for various frequency ranges up to a maximum of 5000 Hz. Data averaging times were as long as 10 minutes, but the integrating time for an individual sample was dictated by the frequency range of interest. Thus, for an upper cutoff frequency of 5000 Hz, the integration time for a single sample was 0.1 sec. If 2048 samples were used in the averaging process, the total sample time would be 204.8 seconds.

Since the integrating time at high frequencies was much shorter than the corresponding reverberation time in the wind tunnel, an alternative approach was used for some of the data reduction. Before being processed by the SD 360, the signals were conditioned by the SD 332 translator using a bandwidth of 100 Hz, and an adjustable center frequency. The conditioned signal could then be processed in the same manner as signals with an upper cutoff frequency of about 100 Hz, i.e., with an integration time of



LOCATION	d m (in.)	θ degrees	U ($\rho = 1915 \text{ N/m}^2$) m/s (ft./sec.)
1	0.36 (14)	43	56.4 (185)
2a	0.61 (24)	22	13.1 (43)
2b	0.25 (10)	45	13.1 (43)
3	0.33 (12.8)	51	11.3 (37)
4a	0.61 (24)	27	4.0 (13)
4b	0.33 (13)	55	4.0 (13)
5	0.64 (25)	16	4.0 (13)

FIGURE 11. DIMENSIONS OF MICROPHONE ARRANGEMENTS IN WIND TUNNEL

5 secs. This integration time is comparable to the reverberation times of 1 to 6 seconds measured in the test section, diffuser and settling chamber [1].

The acoustic measurements were made mainly at a tunnel dynamic pressure of 1915 N/m^2 (40 lb/ft^2), although some measurements were made in the test section at dynamic pressures of 958 N/m^2 (20 lb/ft^2) and 3830 N/m^2 (80 lb/ft^2). Average flow velocities at the test locations are shown in Figure 11 for the 1915 N/m^2 dynamic pressure condition.

5. MEASUREMENTS

Coherence and phase spectra measured in the wind tunnel test section (Location 1) are shown in Figures 12 and 13, respectively, for the frequency range to 5000 Hz. It is seen that the coherence falls rapidly to values less than 0.1, for frequencies above about 400 Hz. The phase angle shows a well defined trend at frequencies below 1500 Hz, but, at high frequencies, the data show large fluctuations. Improved resolutions of the low frequency regime can be obtained by expanding the frequency range, as is done in Figures 14 and 15 where the upper frequency limit is 2000 Hz.

Inspection of the data in Figures 12 through 15 suggests that the general patterns of the coherence and phase spectra are similar to those obtained under the assumption of a combination of propagating and diffuse fields (see, for example, Figures 8 and 9). For instance, curves are shown in Figures 14 and 15 which have been calculated using eqns. (14) and (15) for different values of R , the ratio of diffuse to propagation power spectral densities. For convenience the phase data are presented such that a positive slope indicates downstream propagation. However, before discussing these results in greater detail, data for other locations will be considered.

Figures 16 and 17 present coherence and phase spectra associated with Location 5 in the cross-leg of the settling chamber. Again the coherence decreases rapidly from a value of almost unity to a value less than 0.1. The phase data show a general trend of low frequency (less than 2500 Hz) propagation from fan to test section and high frequency propagation in the reverse direction. However there are some frequency regimes within these subdivisions where the general trend is very distorted.

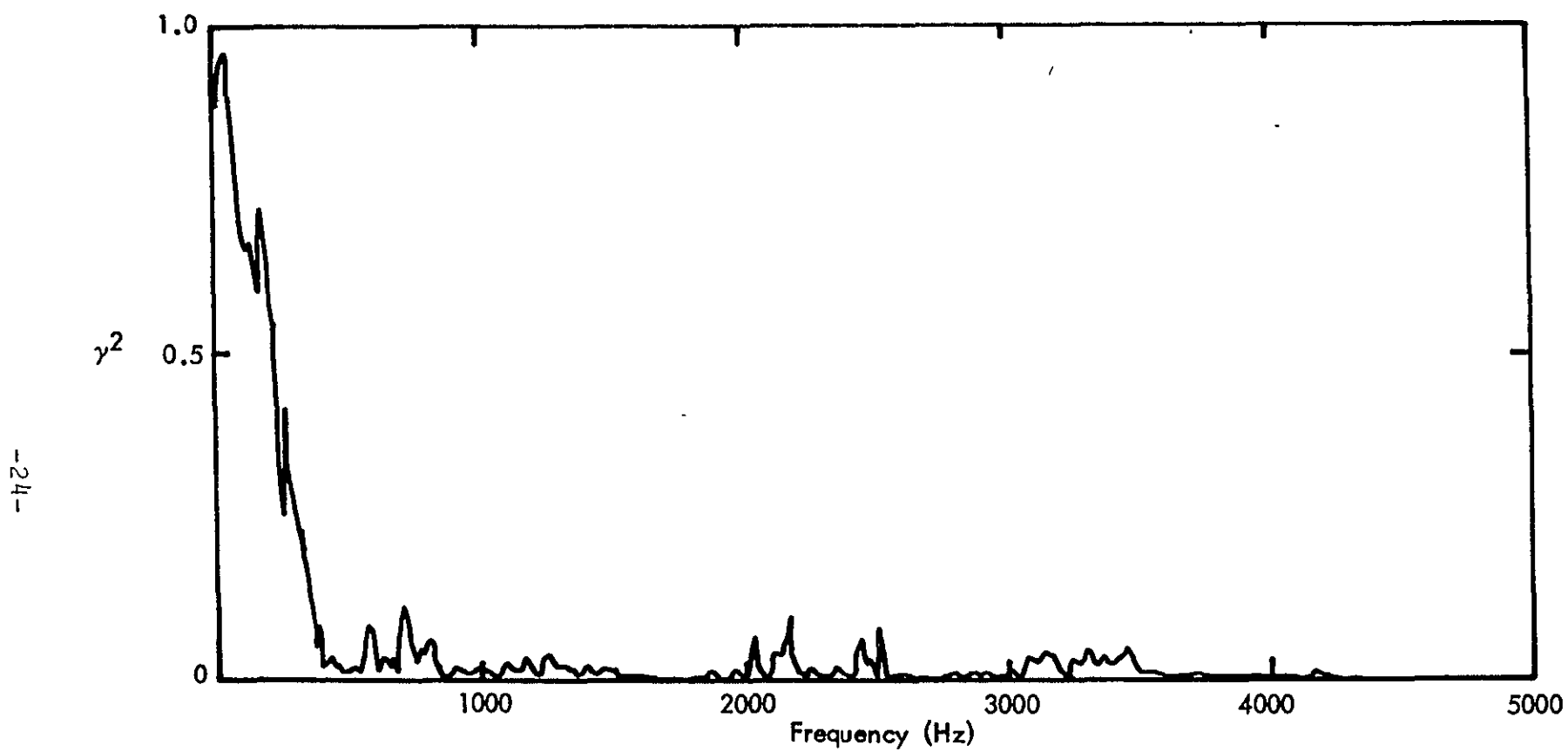


FIGURE 12. COHERENCE SPECTRUM FOR SOUND FIELD IN TEST SECTION (0 - 5000 Hz)

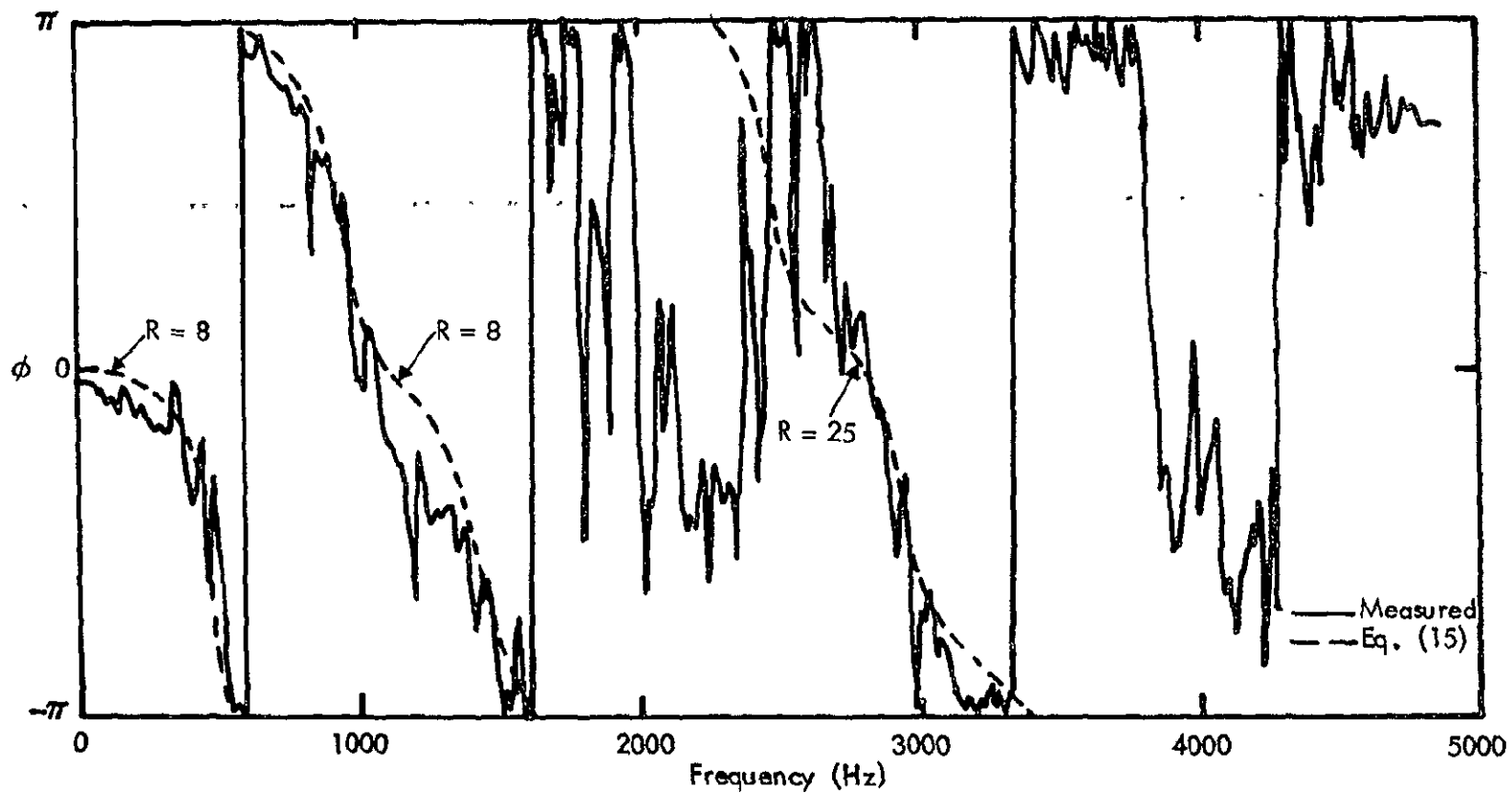


FIGURE 13. PHASE SPECTRUM FOR SOUND FIELD IN TEST SECTION (0 -5000 Hz)

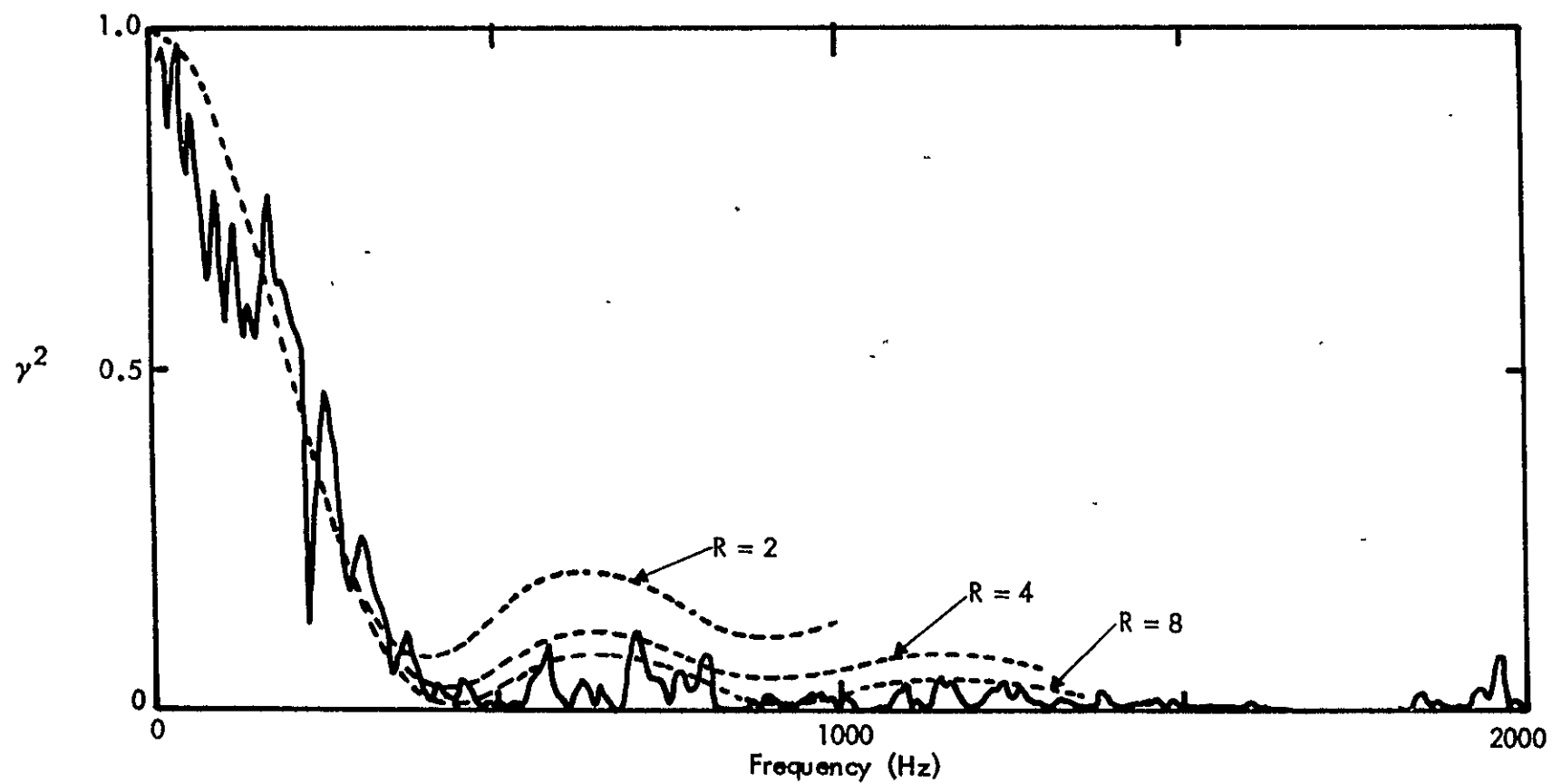


FIGURE 14. COHERENCE SPECTRUM FOR SOUND FIELD IN TEST SECTION (0 - 2000 Hz)

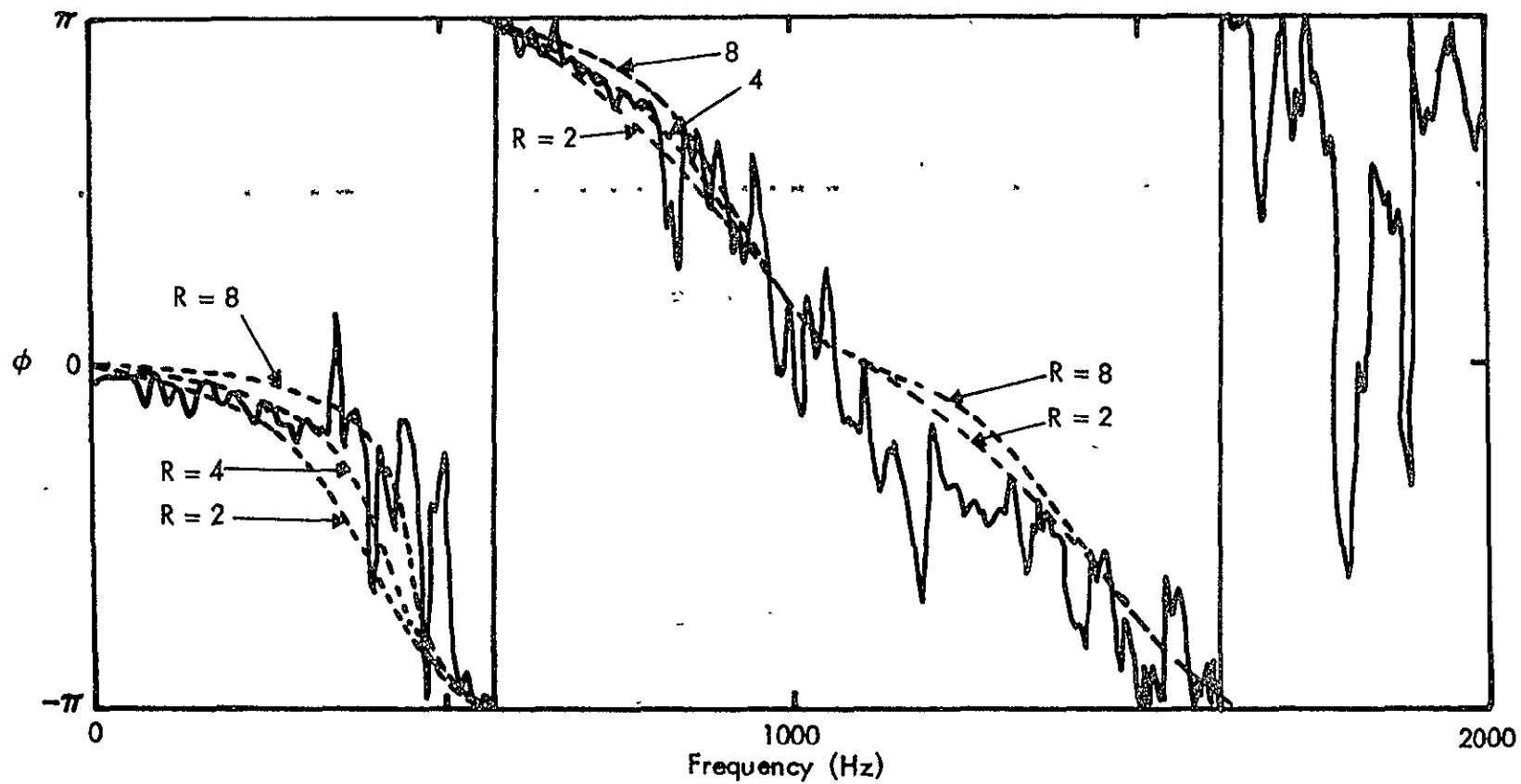


FIGURE 15. PHASE SPECTRUM FOR SOUND FIELD IN TEST SECTION (0 -2000 Hz)

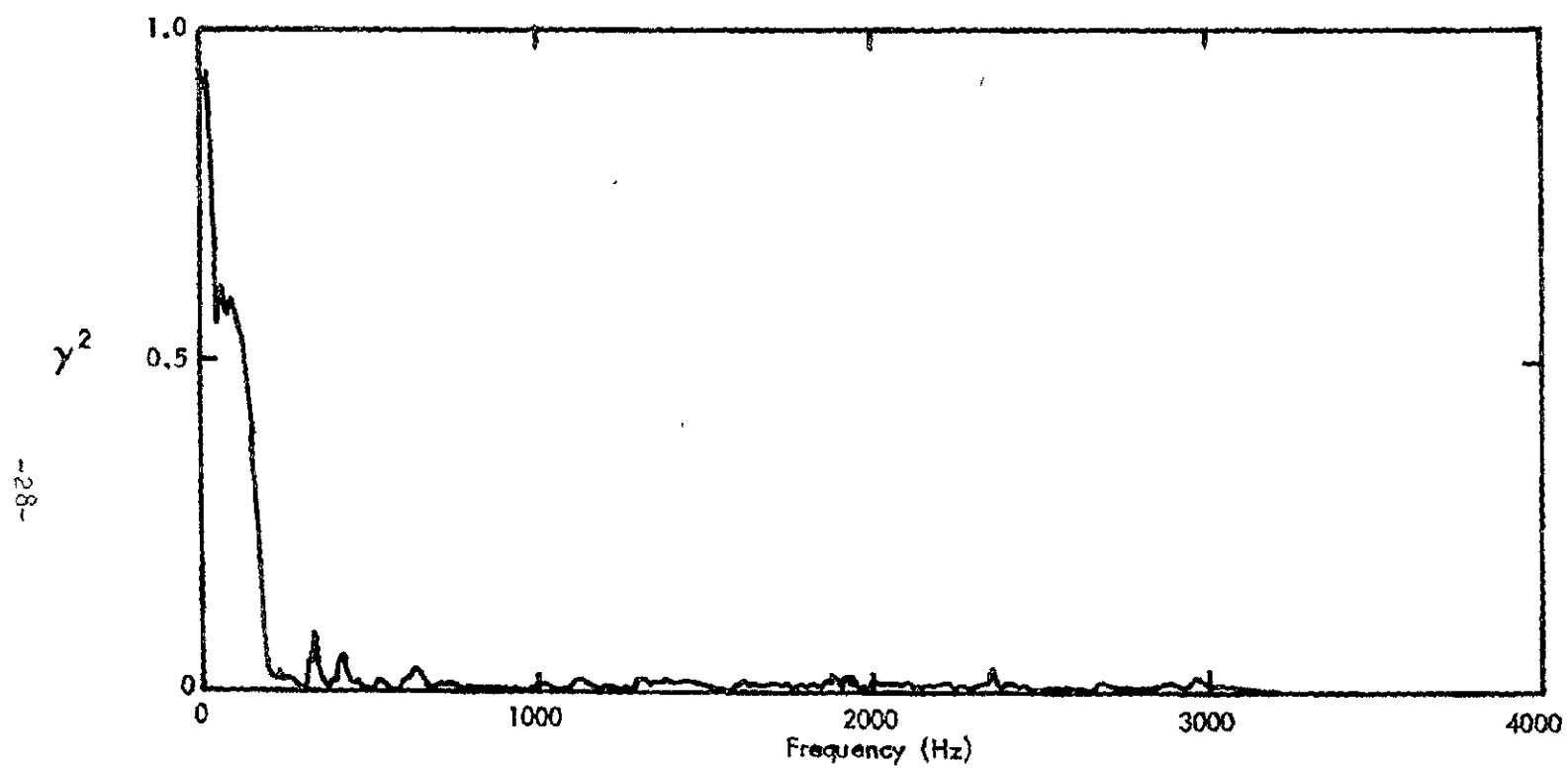


FIGURE 16. COHERENCE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER (LOCATION 5)

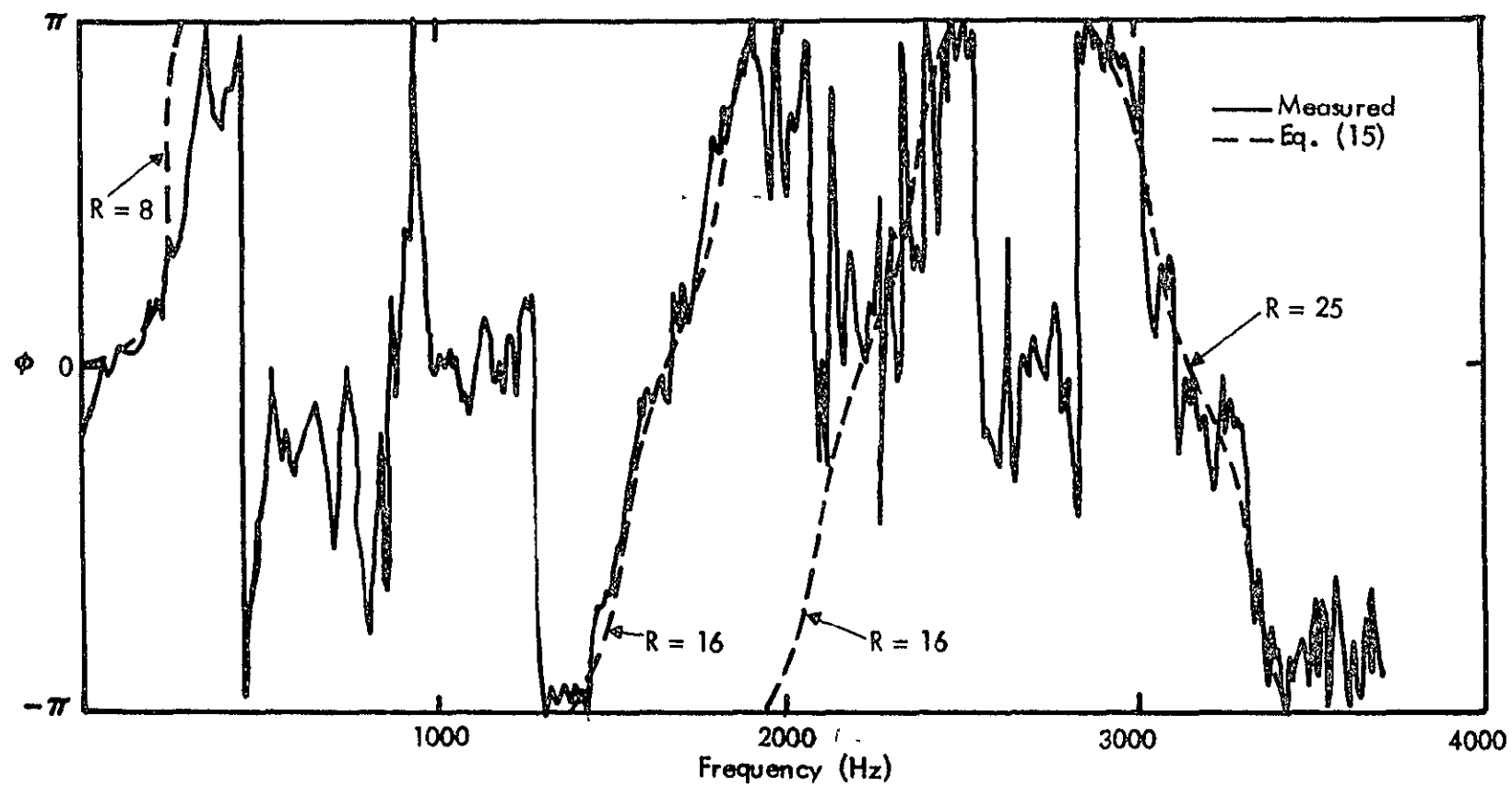


FIGURE 17. PHASE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER (LOCATION 5)

At Location 4, which is just downstream of the air interchange section, the coherence (Figure 18) shows evidence of an oscillatory pattern, although there is still the initial rapid decrease in value. The phase angle spectrum (Figure 19) suggests that there is propagation in the downstream direction, at least for frequencies up to 3500 Hz. These patterns are shown in more detail, for the frequency range to 2000 Hz, in Figures 20 and 21.

Results in Figures 18 through 21 refer to dimensions associated with Location 4(a). If the microphones are brought closer together, as for Location 4(b), the coherence data show no significant changes (Figure 22), but the phase spectrum takes on a fairly strong $0, \pi$ variation and the general propagation trend is much less dominant (Figures 23).

Turning now to the diffuser (Figures 24-29), the coherence data show a significant reduction in the maximum value measured at low frequencies. For example at Location 2 the coherence reaches a maximum value of about 0.8 when the microphone separation distance is 0.61 m (24 inches) (Figures 24) and 0.9 when the separation is reduced to 0.25 m (10 inches) (Figures 26). In the cross leg of the diffuser (Location 3) the maximum coherence is 0.65 (Figure 28), the separation distance being 0.33 m (12.8 inches) in this case. It is believed that these relatively low values of maximum coherence are due to uncorrelated low frequency noise induced by flow fluctuations resulting from flow separation in the diffuser. It is known that low frequency components due to flow separation do exist.

Phase data measured at Location 2 with the 0.61 m (24 inches) microphone separation are similar to results for Location 5, in that they indicate a propagation direction from fan to test section at low frequencies and in the reverse direction at

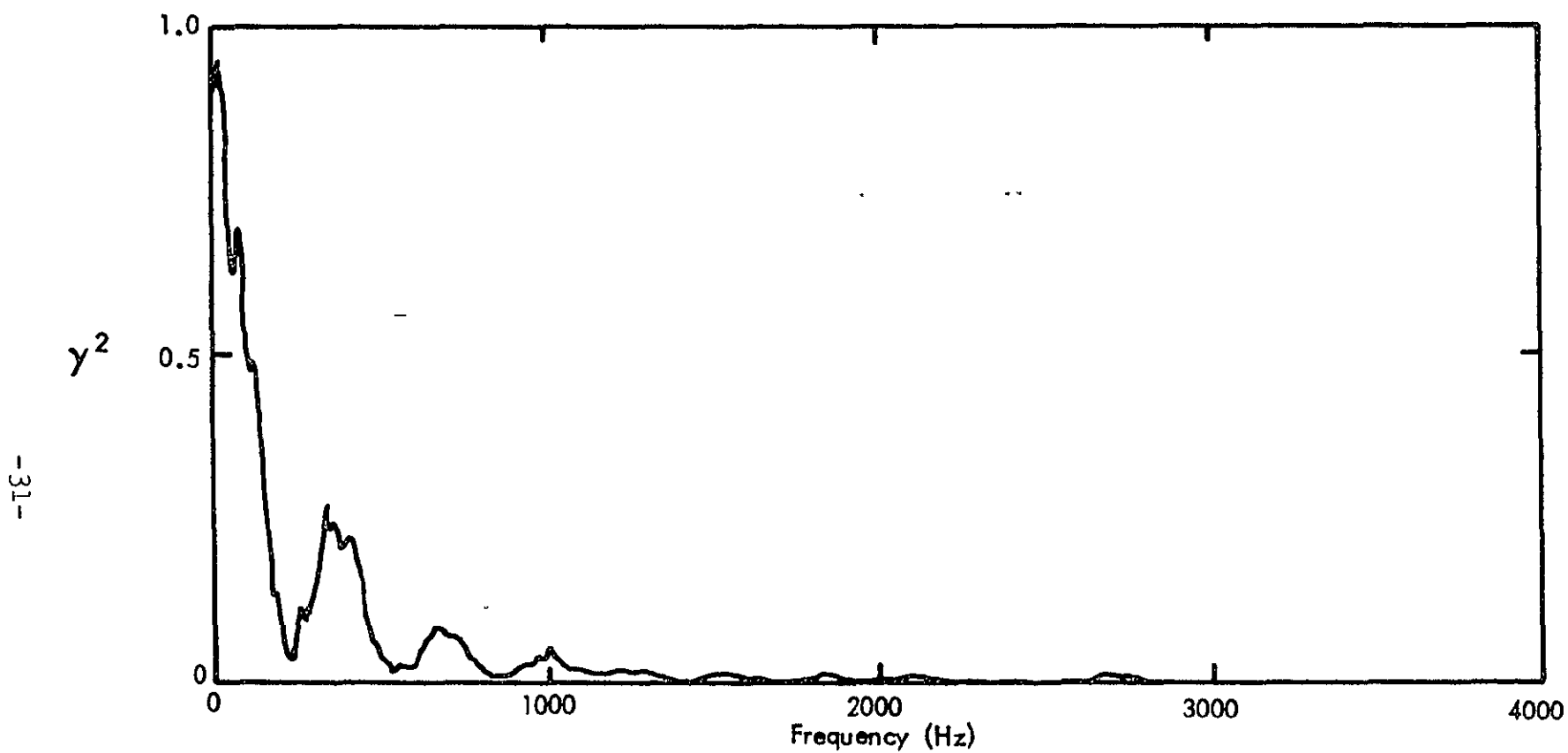


FIGURE 18. COHERENCE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER
(LOCATION 4 a) 0 - 4000 Hz

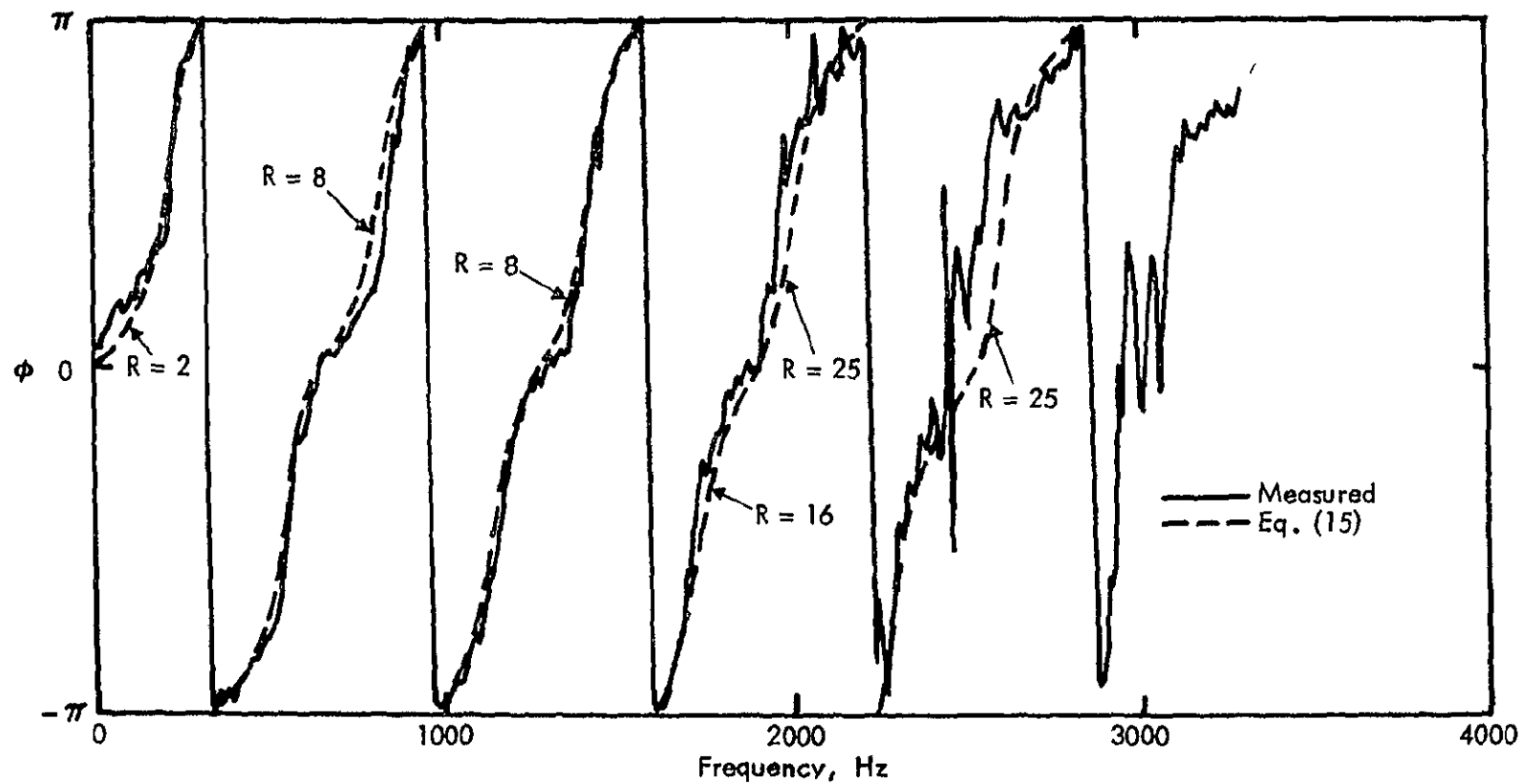


FIGURE 19. PHASE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER (LOCATION 4a)
0-4000 Hz

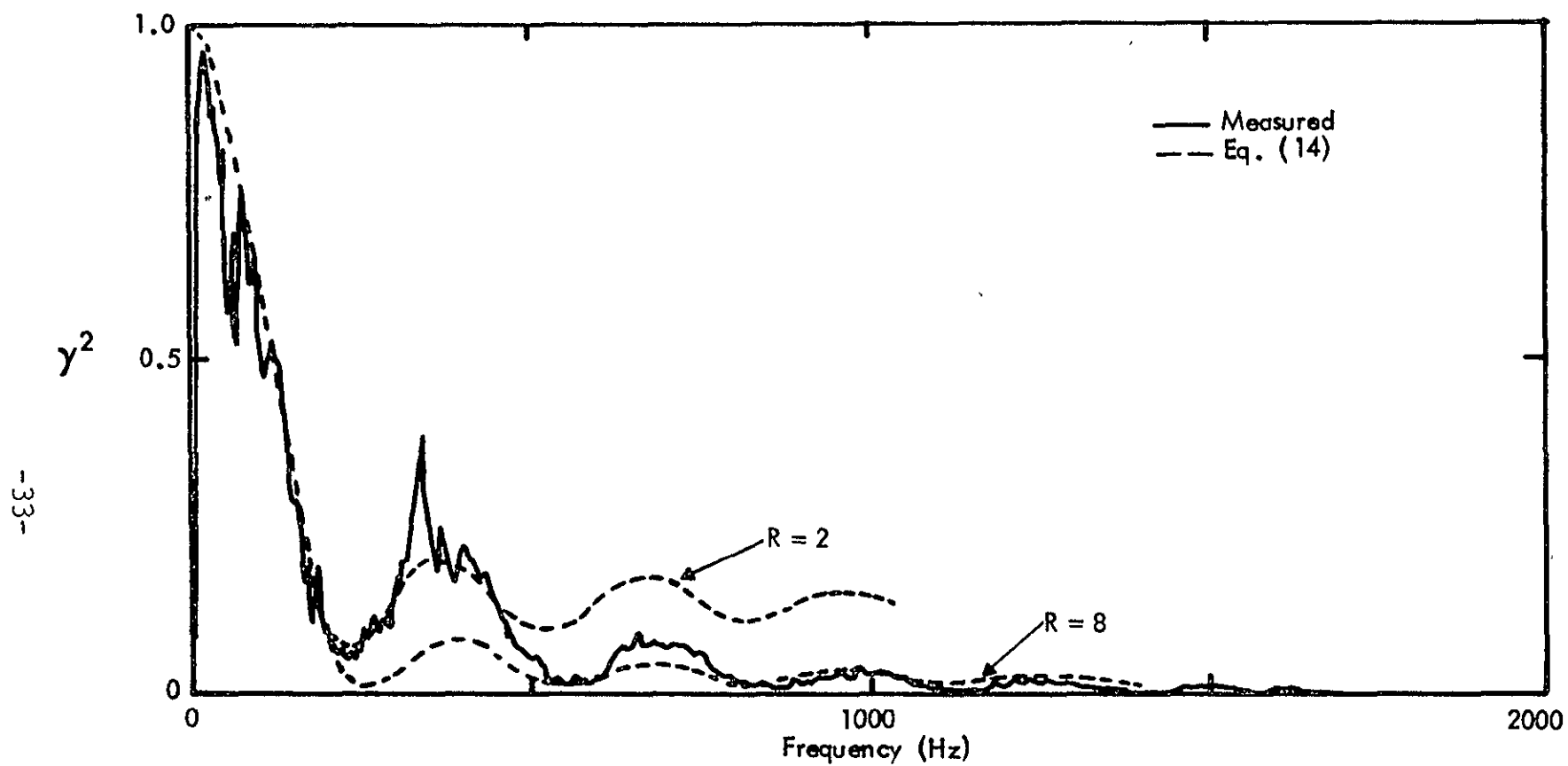


FIGURE 20. COHERENCE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER
(LOCATION 4 a) 0 - 2000 Hz

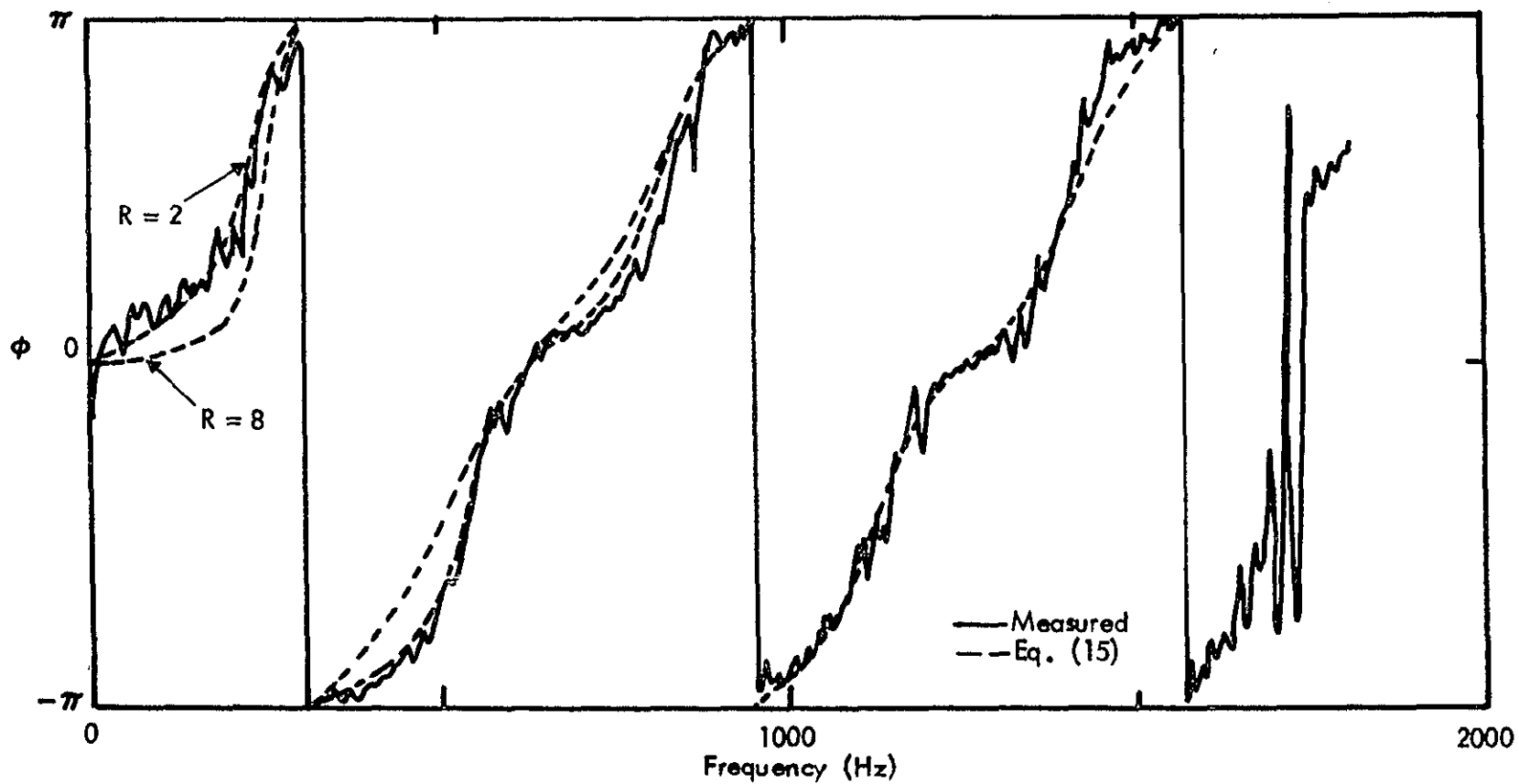


FIGURE 21. PHASE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER
(LOCATION 4 a) 0 - 2000 Hz

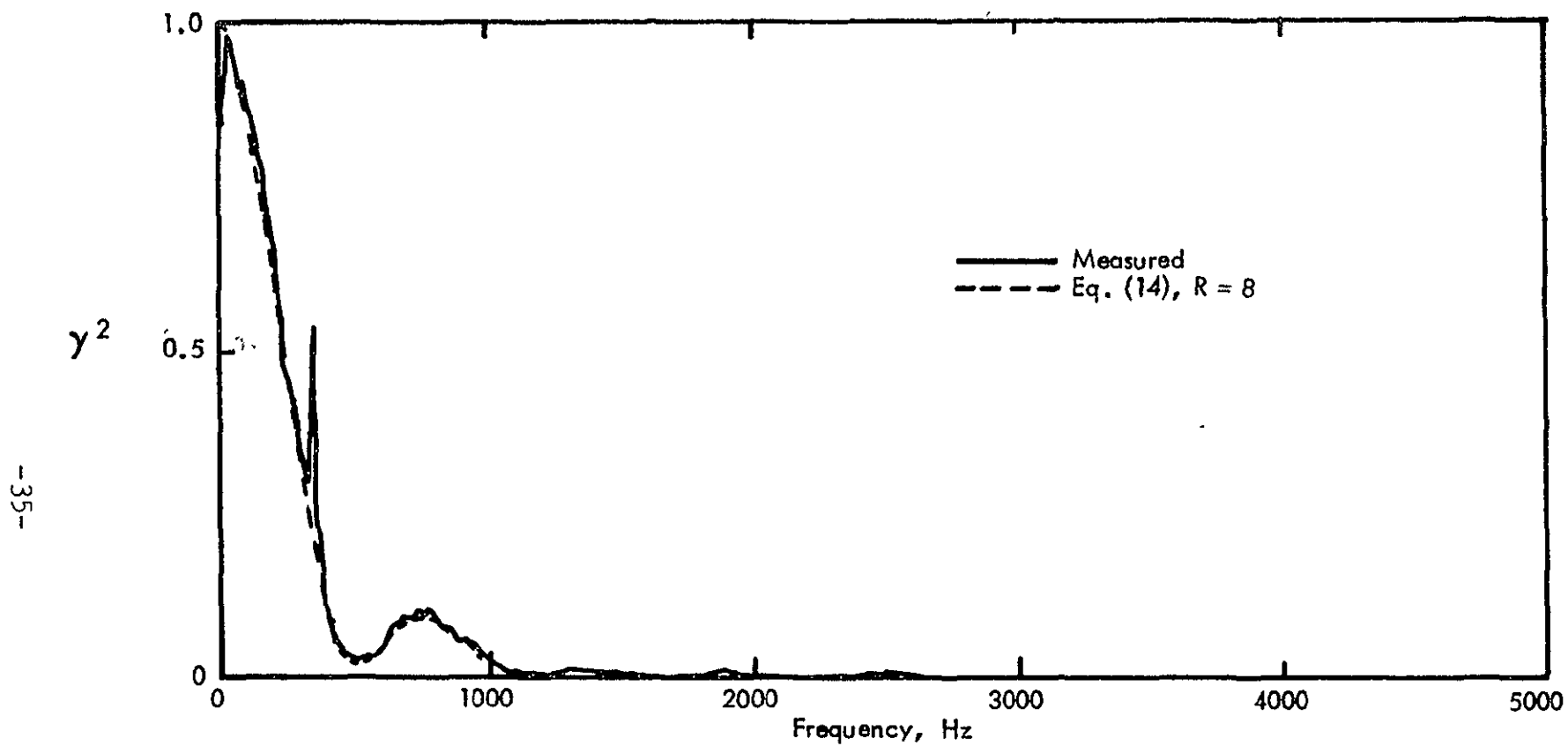


FIGURE 22. COHERENCE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER (LOCATION 4b)
0-5000 Hz

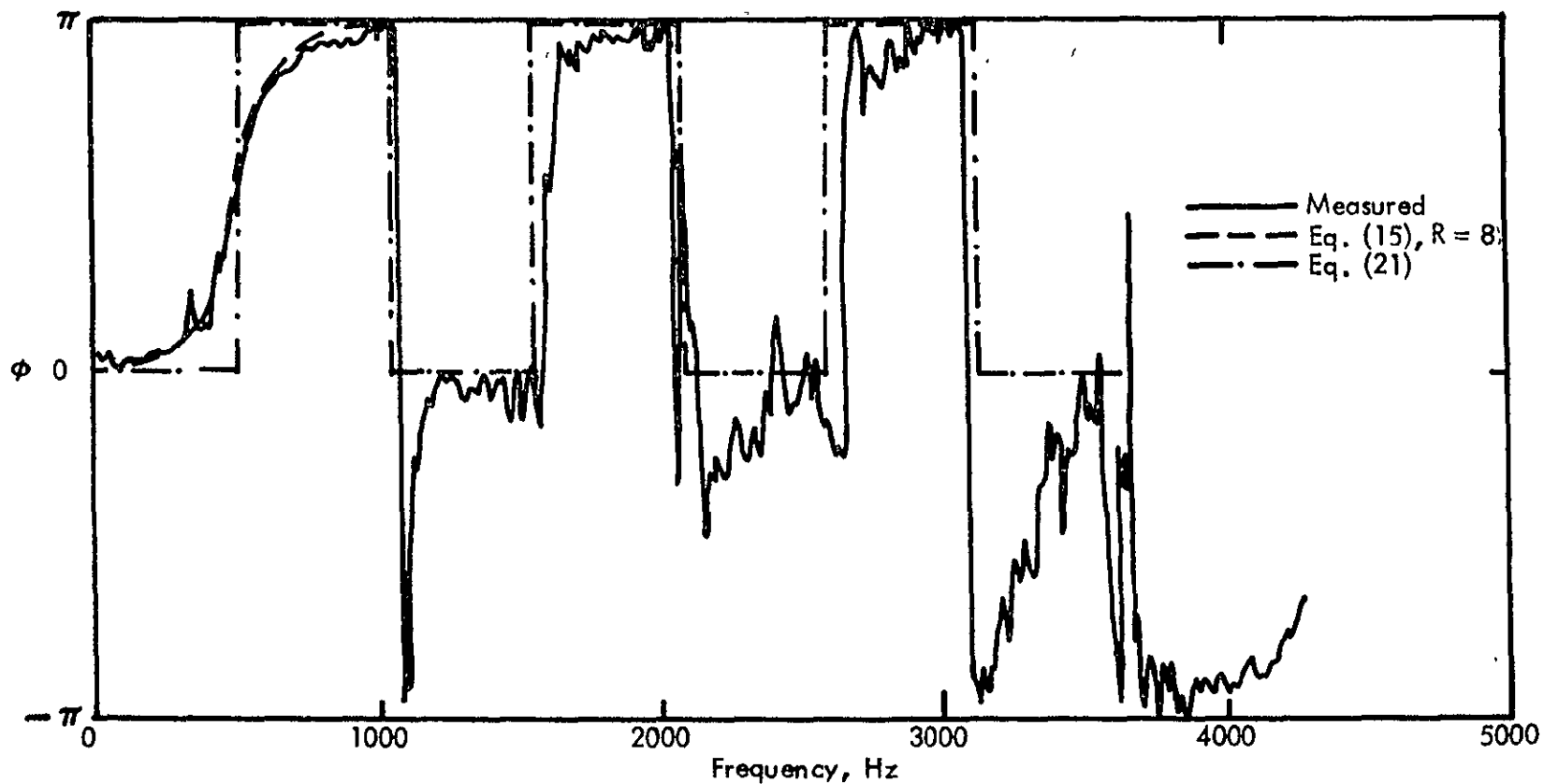


FIGURE 23. PHASE SPECTRUM FOR SOUND FIELD IN SETTLING CHAMBER (LOCATION 4b)
0-5000 Hz

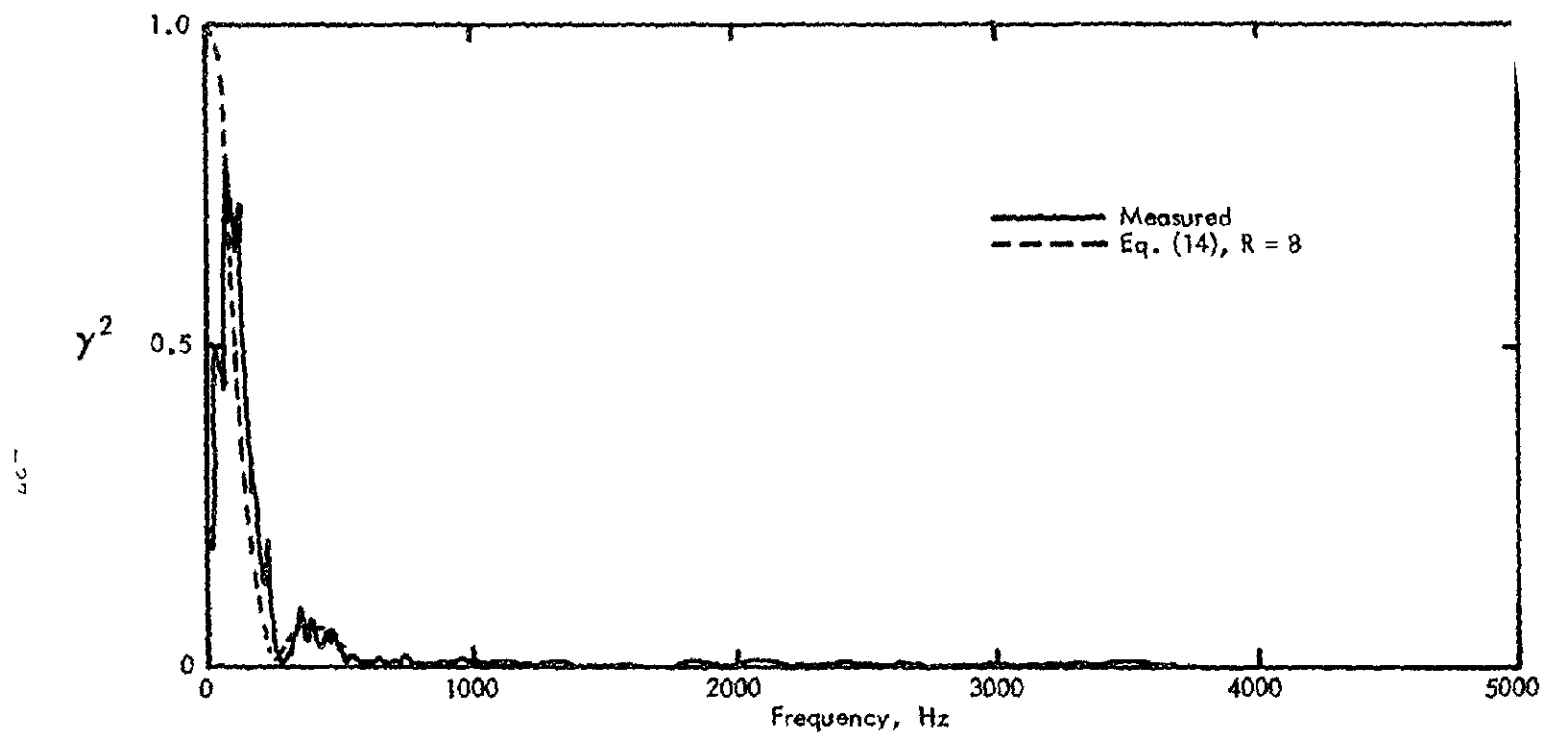


FIGURE 24. COHERENCE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION 2a)

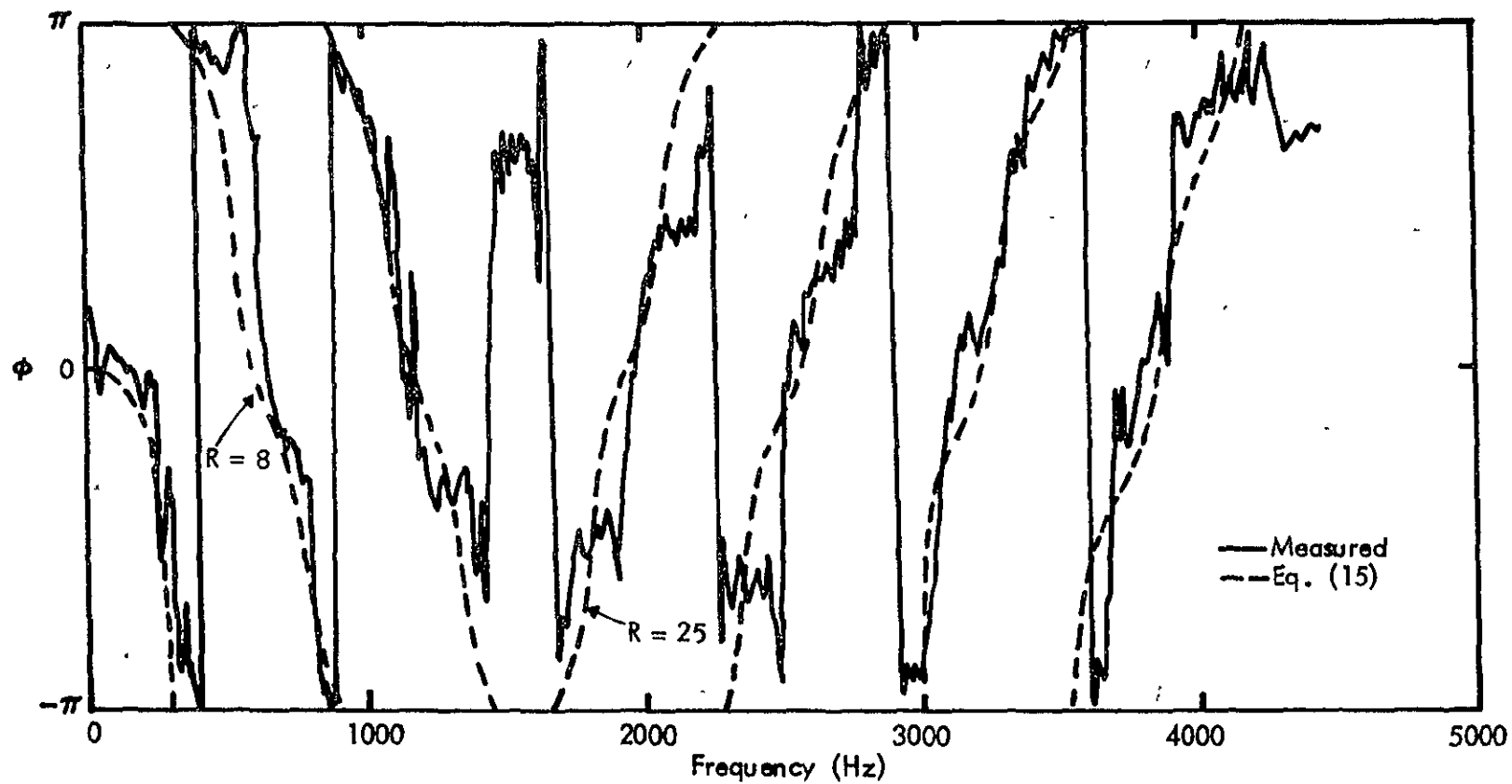


FIGURE 25. PHASE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION 2a)

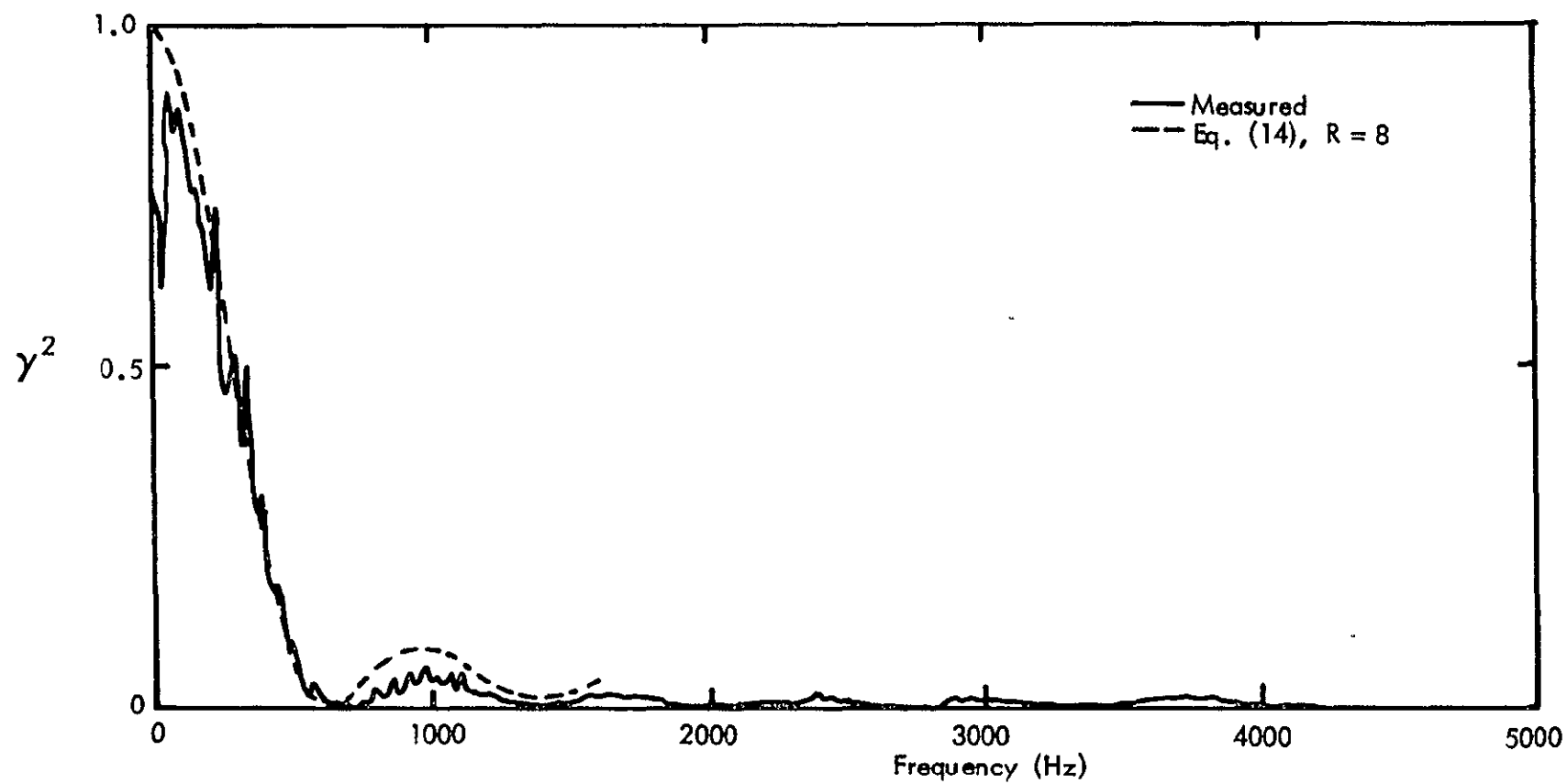


FIGURE 26. COHERENCE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION 2 b)

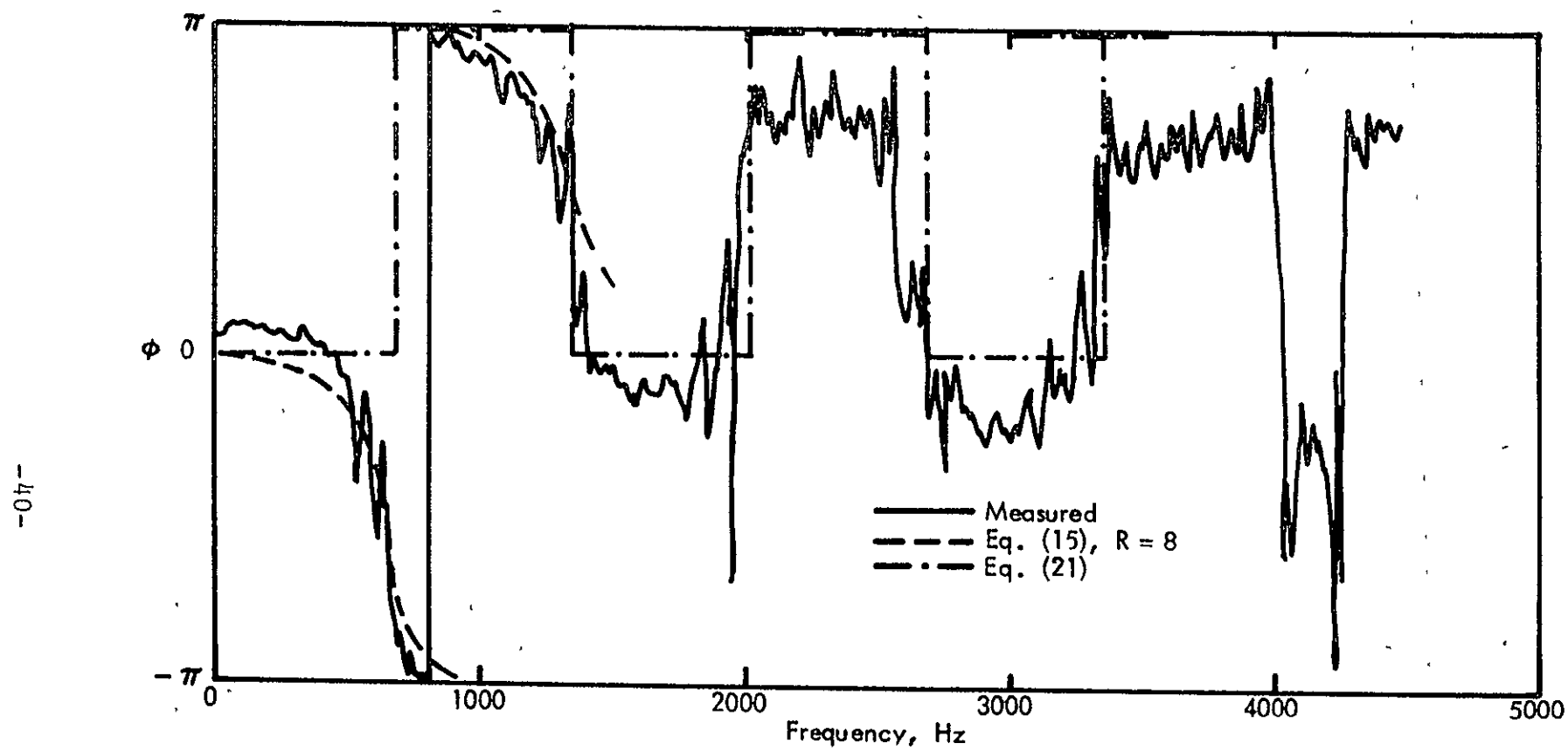


FIGURE 27. PHASE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION '2b')

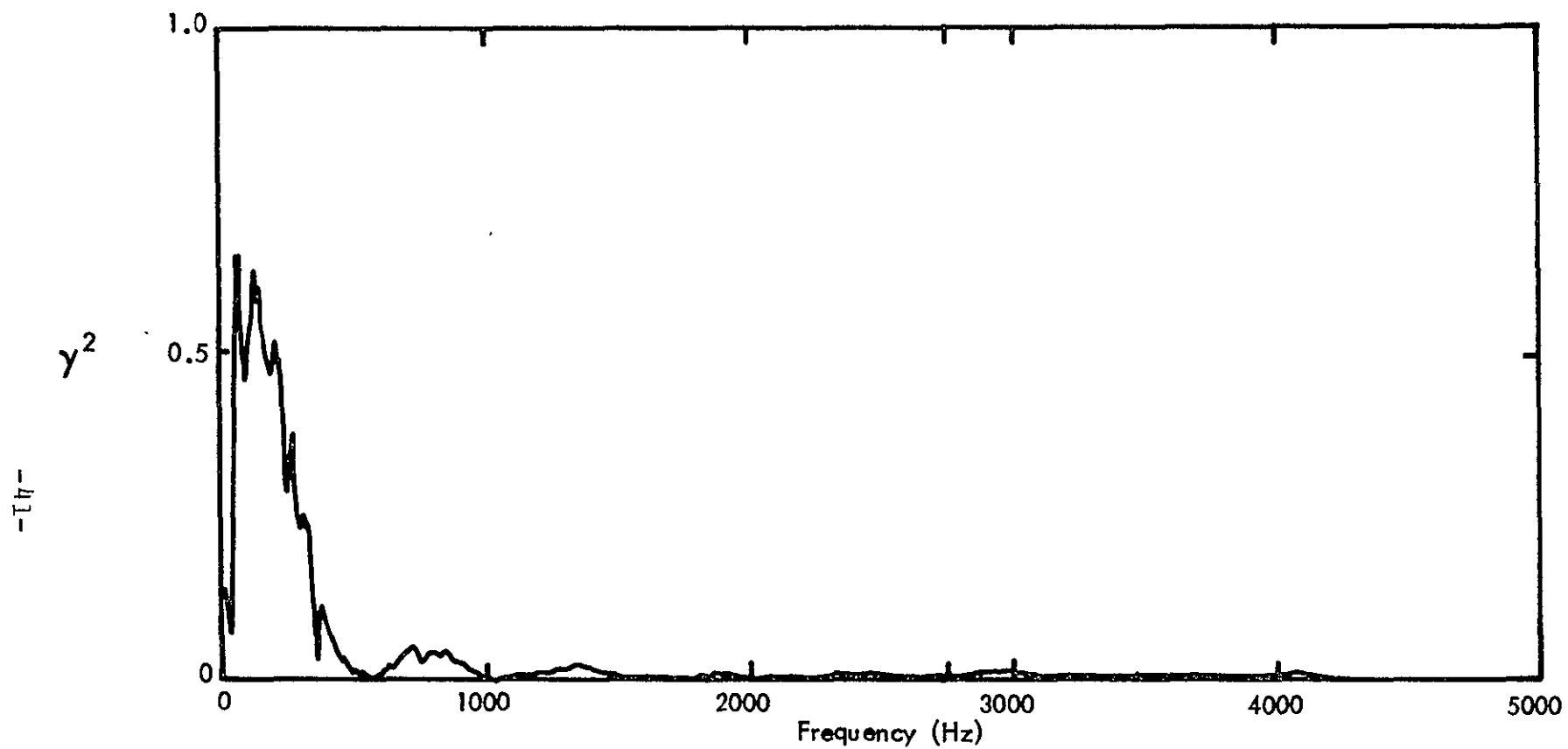


FIGURE 28. COHERENCE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION 3)

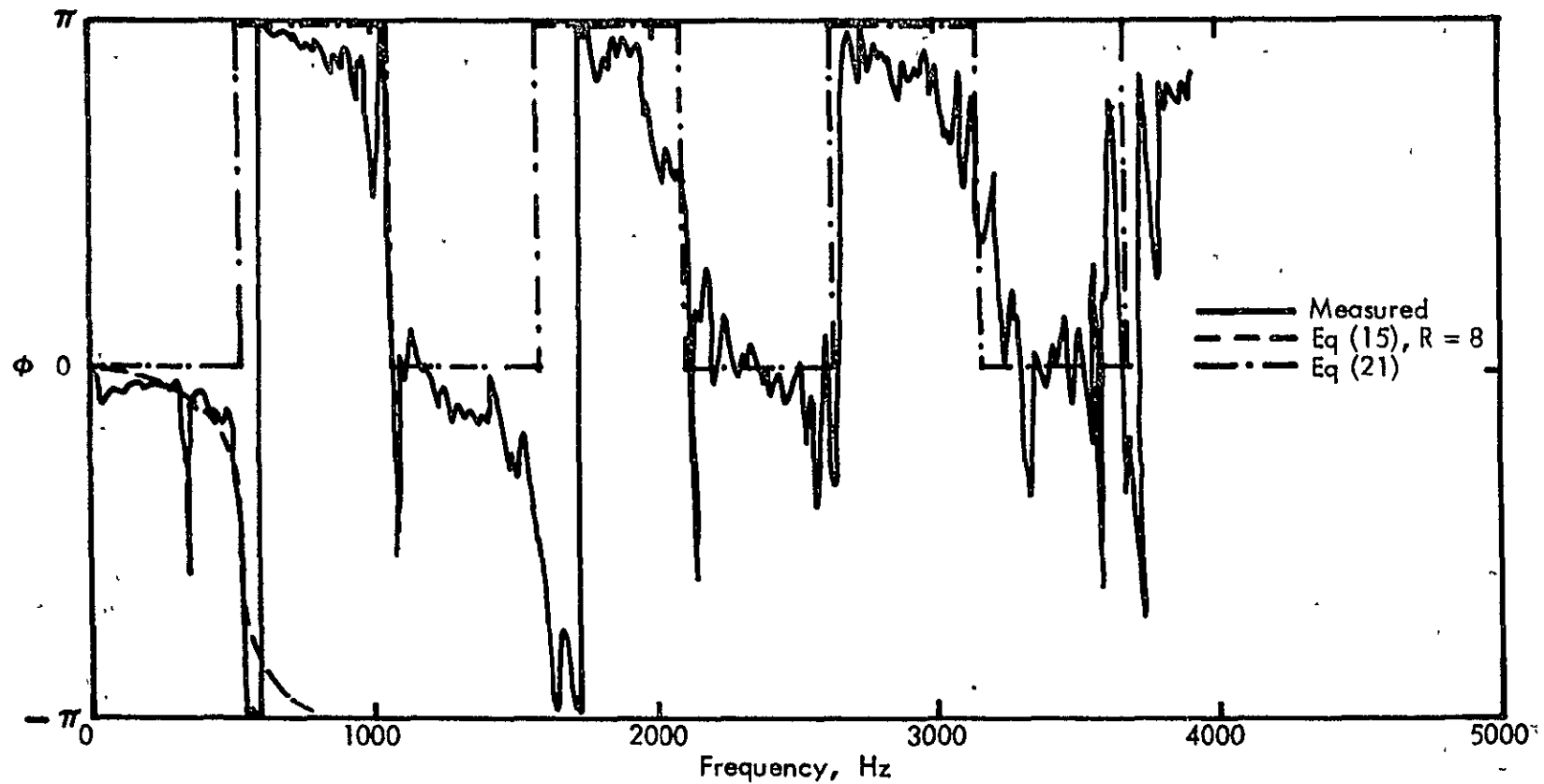


FIGURE 29. PHASE SPECTRUM FOR SOUND FIELD IN DIFFUSER (LOCATION 3)

higher frequencies (Figure 25). In the present case the change occurs at a frequency of about 1500 Hz. However there is a suggestion that a $0, \pi$ variation may be present. This is seen much more strongly in Figure 27 where the microphone separation is reduced to 0.25 m (10 inches).

Coherence and phase data associated with Location 3 in the cross leg of the diffuser are shown in Figures 28 and 29. The microphone separation distance is 0.33 m (12.8 inches) in this case and phase spectrum again shows a significant $0, \pi$ type variation.

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6. DISCUSSION

The coherence spectra measured at the five test locations all show similar characteristics. They have maximum values at low frequencies, and decay rapidly as frequency increases. At higher frequencies the spectra have an oscillatory nature which is similar to that predicted for a combination of diffuse and propagating fields, provided that the ratio, R , of diffuse to propagating power spectral densities is allowed to vary with frequency. It has been seen earlier (e.g., Figure 5) that an oscillatory coherence function can also be obtained from a combination of two propagating fields. However in this case the periodicity of the analytical representation differs from the measured pattern, and the analytical model coherence does not predict the observed coherence decay as frequency increases.

Incoherent noise does not make a significant contribution to the microphone signals in the test section or in the settling chamber. This can be seen in two ways. At low frequencies the measured coherence is approximately unity, indicating that the incoherent noise level is low. Then at higher frequencies, when a combination of diffuse and propagating waves is assumed and an analytical representation is fitted to the experimental data, the values of R which give the best fit to the data are approximately the same for coherence and phase. If there was a significant contribution from incoherent noise, then a smaller value of R would be required to fit the analytical representation to the measured coherence data than would be required for the phase spectrum.

There does, however, appear to be low frequency, incoherent noise present in the microphone signals for the diffuser locations, since the measured coherence is much lower than unity. This

loss of coherence has been attributed to low frequency turbulence which is uncorrelated from microphone to microphone. The turbulence results from flow separation on the wall of the diffuser. Such flow separation is known to be present in the diffuser, and large amplitude, low frequency fluctuations have been observed in signals from microphones in the diffuser, but not in signals from microphones at other locations.

Coherence spectra presented in the preceding figures were obtained using integration times of 0.1 to 0.5 sec., values which are an order of magnitude smaller than the reverberation times in the tunnel. However the coherence values showed no measurable change when an integration time of 5 seconds was used. This integration time is similar to the measured reverberation times in the tunnel.

Using a single source in a reverberant room, Scharton [5] has investigated the effect of record length on the measured coherence. Results from the investigation are plotted in Figure 30, where it is seen that the measured coherence is greater than about 0.9 if the record length is greater than the reverberation time. The longer the record length relative to the reverberation time, the closer is the measured coherence to the ideal value of unity.

In the 7x10 wind tunnel, high coherence was measured when a single acoustic source was used, the tunnel was not operating, and the signals were integrated for times equal to, or greater than, the tunnel reverberation time. For example, Figure 31 compares coherence values obtained from two arrangements using an acoustic source, with values measured during low speed operation of the tunnel. In one of the arrangements an acoustic source was located in the diffuser and the microphones were in the test section. For the second test the noise source was near the tunnel drive fan, one microphone was at the fan, and the other in the test

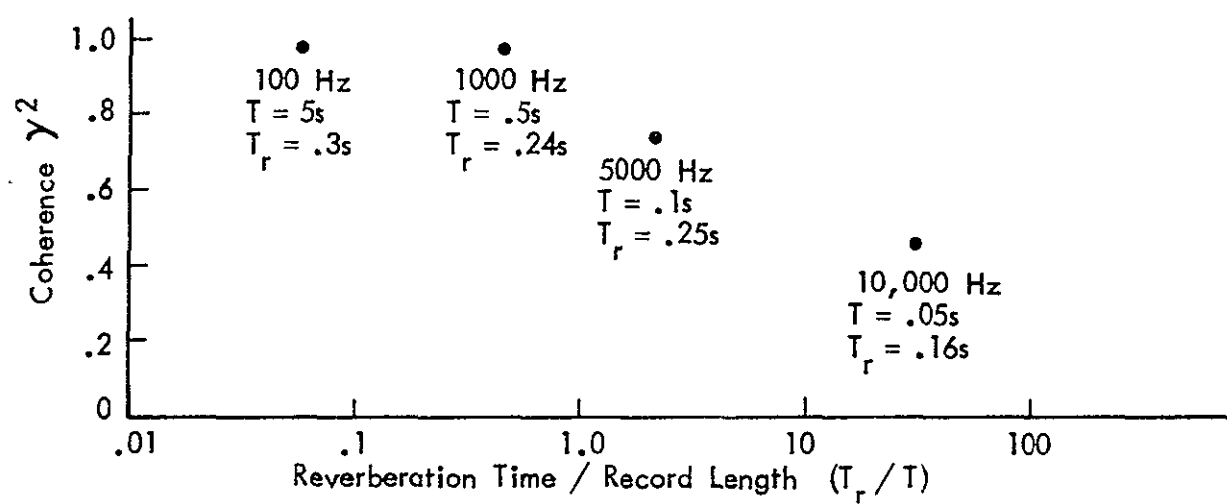


FIGURE 30. EFFECT OF RECORD LENGTH ON MEASURED COHERENCE FOR A SINGLE SOURCE IN A REVERBERANT ROOM

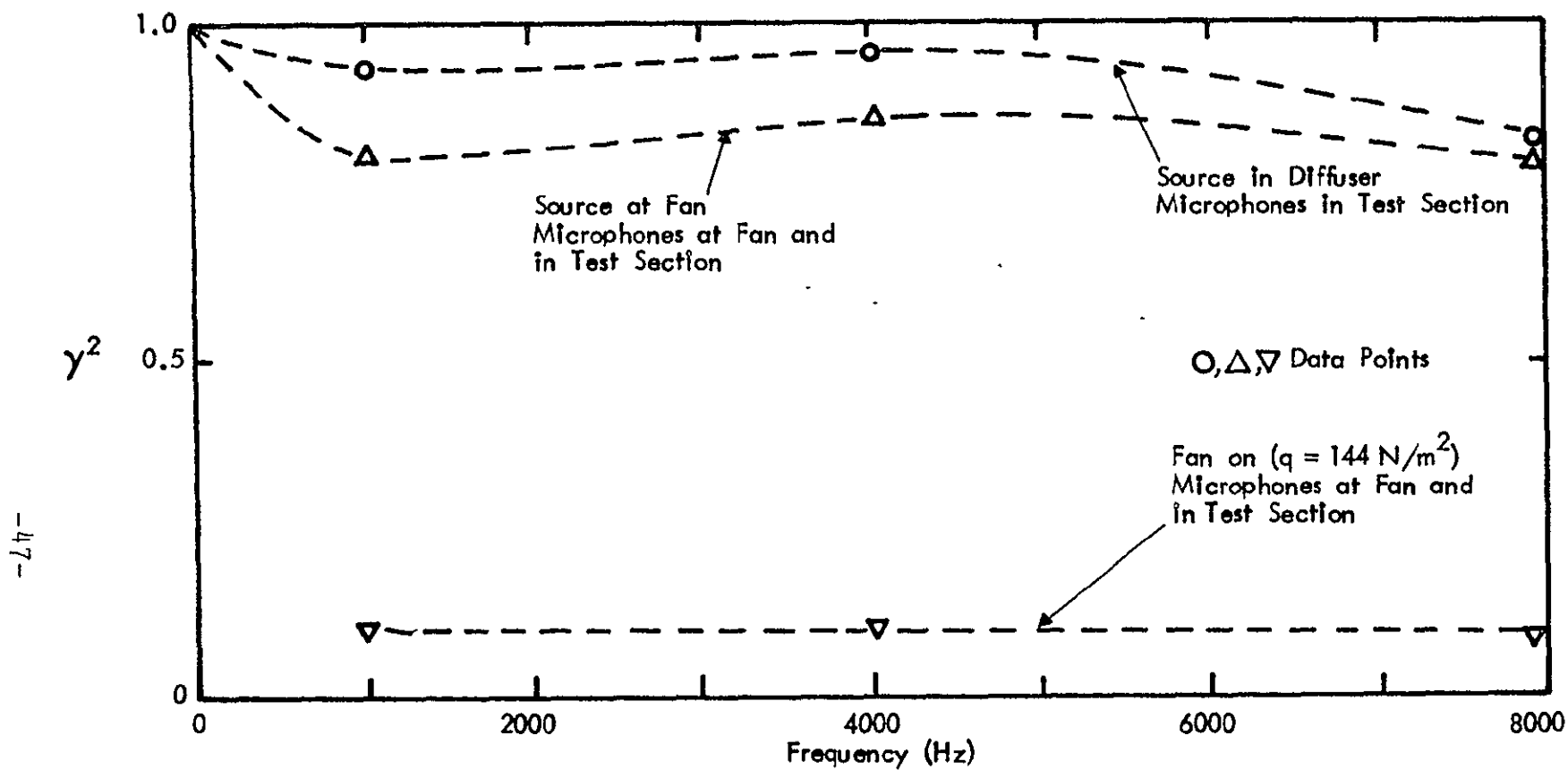


FIGURE 31. COHERENCE SPECTRA FOR SOUND FIELD FROM A SINGLE SOURCE

section. Coherence was measured at three frequencies, 1000, 4000, and 8000 Hz, and as shown in Figure 31, the coherence maintained values of at least 0.8 when the single noise source is used. In contrast, when the tunnel drive system provided the noise source, even at very low speeds, the coherence fell by about an order of magnitude to a value of 0.1, a result that is similar to measurements in the test section when the flow speeds are higher. This would suggest that the noise field measured in the test section during normal tunnel operation is not that of a single source in a reverberant environment but is that due to several incoherent sources.

The phase spectra measured at the five test locations in the tunnel show two different characteristics. In one case the pattern is that of a propagating field with some modification due to diffuse, reverberant or other factors. The basic slope of the phase spectrum is that associated with sound propagation in the upstream, or downstream, direction with the appropriate trace velocity being the resultant of the velocity of sound and the flow velocity. Thus the phase changes by π when the frequency changes by an increment Δ_1 where

$$\Delta_1 = \frac{(c_o \pm U)}{2d \cos \alpha} . \quad (19)$$

In the second case the phase spectrum assumes approximate values of 0 and π , although there are some deviations from this pattern. The alternating 0 and π values exist for a given frequency increment, Δ_2 , which is given, approximately, by

$$\Delta_2 = c_o/2d \quad (20)$$

and the measured phase can be represented by

$$\left. \begin{aligned} \phi &= 0 & 2n\Delta_2 < f < (2n+1)\Delta_2 \\ &= \pi & (2n+1)\Delta_2 < f < (2n+2)\Delta_2 \end{aligned} \right\} n = 0, 1, 2 \dots (21)$$

The $(0, \pi)$ pattern appears in the most distinct form when there is a significant difference between Δ_1 and Δ_2 . For example, values of the frequency increments associated with Figures 23, 27, and 29 are given below:

	Δ_1 (Hz)	Δ_2 (Hz)	Δ_1/Δ_2
Figure 23	912	517	1.76
Figure 27	950	672	1.41
Figure 29	812	525	1.55

Conversely, the propagating pattern is prominent when Δ_1 and Δ_2 have similar values, as indicated below:

	Δ_1 (Hz)	Δ_2 (Hz)	Δ_1/Δ_2
Figure 15	548	480	1.14
Figure 19	318	280	1.14
Figure 25	290	280	1.04

It should be noted that, in fact, the situation is not as clearly defined as is implied above. For example, even when the $(0, \pi)$ pattern is well developed, there is still a strong convected pattern at low frequencies, such as is the case in Figures 23 and 27.

When the propagating pattern is present, analysis can be performed under the assumption that the acoustic field is a combination of propagating and diffuse components. Calculated curves for coherence and phase are shown in the appropriate figures, for several values of R substituted in eqns. (14) and (15).

For the test section, the analytical representations of equations (14) and (15), with $G_n = 0$, follow the measured coherence and phase functions if $R = 5$ for frequencies below 1000 Hz, and R is approximately 8 for frequencies above 1000 Hz. Measurements were also made at two other flow conditions, and corresponding phase spectra are shown in Figures 32 and 33. For a flow velocity of 39.9 m/s (131 ft/sec) the best data fit is obtained when R is approximately 8, and 79.9 m/s (262 ft/sec) the appropriate value of R is about 4. Thus there is a general trend of R decreasing as flow velocity increases.

Now consider the measuring locations in the diffuser and settling chamber. Again it is assumed that the sound field is a combination of diffuse and propagating components and that the ratio R of the two power spectral densities can be estimated by use of Equations (14) and (15). For the diffuser data it is found that $R \approx 8$, at least for frequencies below 1500 Hz. At the air interchange, Location 4, the value of R appears to increase with frequency having a value of 2 for frequencies below 300 Hz, 8 for the frequency range 300 to 1400 Hz, 16 from 1400 to 1800 Hz and 25 from 1800-2200 Hz.

This analysis shows that, for the frequency regime below about 1500 Hz, the value of R , which best describes the experimental data, lies in the range of 5 to 8 irrespective of the measurement location. This implies that the diffuse field has a power spectral density which is 5 to 8 times as large as that for the propagating field.

There are at least two possible interpretations of this result. The diffuse field could be generated within the neighborhood of each measurement location, or it could result from incoherent sources some distance from the microphones, for example, at the

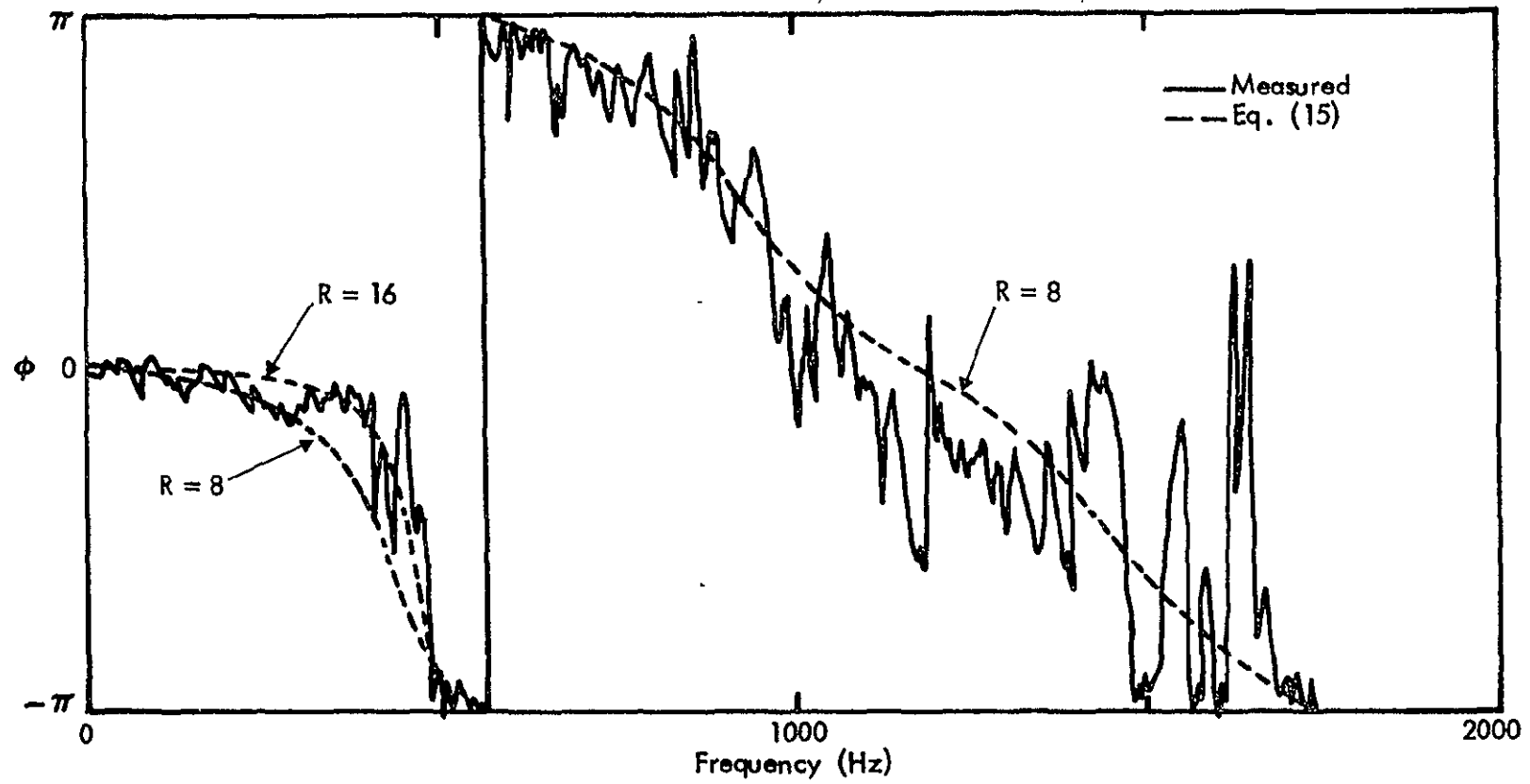


FIGURE 32. PHASE SPECTRUM FOR SOUND FIELD IN TEST SECTION ($q = 958 \text{ N/m}^2$)

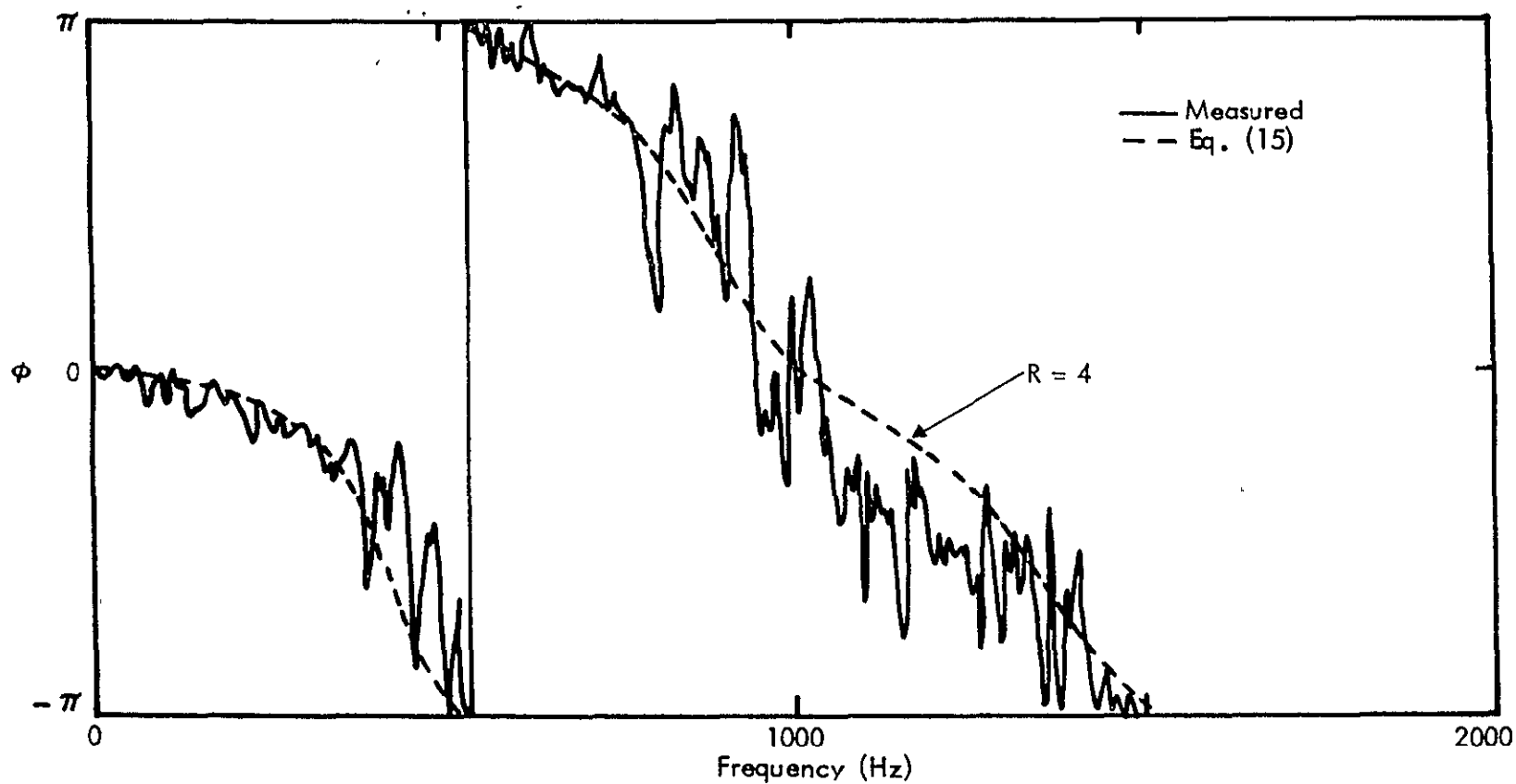


FIGURE 33. PHASE SPECTRUM FOR SOUND FIELD IN TEST SECTION ($q = 3830 \text{ N/m}^2$)

fan. Local generation does not appear to be a likely explanation because of the wide differences in flow velocity from location to location. In the extreme, the flow velocity in the test section is 14 times larger than the velocity in the settling chamber, but the sound pressure levels differ by less than 10 dB. Consequently it is more likely that the diffuse field results from incoherent sources at other locations in the tunnel.

The dominant direction of propagation can be obtained from the slope of the phase spectrum. For convenience, the phase data in this report are presented such that a positive slope indicates downstream propagation of the sound field and a negative slope represents upstream propagation. The measurements show that low frequency noise propagates from the fan in the downstream direction to the air interchange and settling chamber, and in the upstream direction to the diffuser and test section. The finding that the low frequency sound in the test section travels via the diffuser rather than the settling chamber is consistent with a result from a previous study [1] that acoustic energy did not pass easily from settling chamber to test section because of the large reduction in cross-sectional area.

As the frequency of interest increases, the propagation characteristics show a significant change. Thus, above about 1700 Hz, the sound field in the diffuser has a downstream propagation direction, and above about 2800 Hz, the sound field in the settling chamber propagates upstream. This result can be interpreted in terms of the dominant high frequency noise sources being located in the test section rather than at the fan.

7. CONCLUSIONS

On the basis of the coherence and phase measurements for the sound field in the wind tunnel, it is concluded that the dominant low frequency sound in the test section is generated in the neighborhood of the fan, and the high frequency sound is generated locally in the test section itself. The boundary between low and high frequency appears to be in the 1500 to 2000 Hz range. It is possible that some noise is generated within the first part of the diffuser but this cannot be determined from the present tests.

The characteristic patterns of the measured coherence and phase spectra are similar to those predicted by an analytical model which assumes diffuse and propagating components, with incoherent noise in some cases. The ratio of diffuse to propagating power spectral densities is approximately 8 when the tunnel is operated at a dynamic pressure of 1915 N/m^2 (40 lb/ft^2). However the present simplified analysis does not take fully into account the influence of tunnel reverberation. Further analysis of this effect is required.

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